D0 ENGINEERING NOTE

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D0 SILICON UPGRADE

Thermal Conductivity Measurements of Thermal Compounds

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1.0 Introduction

The thermal characteristics of the adhesives and greases used in the D0 Silicon Detector must be well understood in order to insure adequate thermal performance among all 648 individual silicon wafers. The thermal conductivity and joint resistance of several types of adhesives and greases have been measured to provide a check with manufacturers' published values. This paper describes D0 Silicon Upgrade thermal design parameters, the thermal conductivity test measurement method, the thermal compounds, and test results.

The measured thermal conductivities range from 0.5 - 1.4 W/m °C for thermally and electrically conducting adhesives, 0.5 - 1.0 W/m °C for thermally conducting adhesives, 0.2 - 0.3 W/m °C for thermally insulating adhesives, and 0.6 to 0.9 W/m °C for greases.

2.0 Design Parameters

The silicon wafers will be operated in a range of 5 to 20°C to limit leakage current due to radiation damage. These limitations can be achieved if the temperature rise through any one bond is held to 2-3°C [1]. This temperature rise is calculated from the following formula:

$$R = \frac{(T_1 - T_2)}{Q} = \frac{x}{kA} \qquad \text{Eqn. 1}$$

where: T_1 = Temperature at point 1 [C]
T_2 = Temperature at point 2 [C]
Q = heat input [W]
x = joint thickness [m]
k = thermal compound conductivity [W/m C]
A = joint area [m^2]
R = Thermal resistance [°C/W]

Thus, the thermal resistance can be minimized either by a large "k" (thermal conductivity) or a small "x" (joint thickness). The conductivity of an adhesive can be increased by filling it with solids of greater conductivity which make random thermal contact from one side of the bond to the other. The joint thickness can be minimized by using a product with low viscosity. For these reasons then, a variety of thermal compounds were tested.

The temperature rise across successive joints adds in series. There are two joints between the barrel bulkhead and silicon, three joints between the disk cooling channel and silicon, and, for both disks and barrels, up to three additional joints between the silicon and chips.

The requirements for thermal compounds vary for different joints. Joints which contact the silicon wafer must be large enough to insure that there is no electrical interference. R. Lipton determined that a 25 micron (0.001") bond thickness is acceptable. Also, adhesives in contact with the silicon must be chemically compatible with it; manufacturer's listed ionic impurity levels serve as an indicator of this. Bonds between wedge and disk support structure need not be strong because screws will be used to do the fastening. However, bonds between ladder and bulkhead probably perform the function of fastening so they must be strong, but also removable to facilitate the assembly process. Another criteria is electrical conductivity. Bonds which contact the chips and the cooling channel must be electrically conductive; bonds which contact the silicon or kapton jumpers must be electrically insulating; bonds between the beryllium substrate and MCM may or may not be electrically conductive.

3.0 Products Tested

Based on the above requirements, the thermal compounds under consideration were categorized in the following way:

Adhesives:
- TEC = Thermally and Electrically Conductive
- TC = Thermally Conductive
- TI = Thermally Insulating

Greases:
- TEC = Thermally & Electrically Conductive
- TC = Thermally Conductive

Products which were tested are listed below by category. Samples which were removable with the aid of fixturing are noted. Samples which were undesirable because of high viscosity or cure cycle are noted.

Adhesives:
1. Chomerics (A Grace Co.) - Cho-Bond 584 [TEC, Ag filled]
2. Emmerson & Cummings (A Grace Co.) - Eccobond 59C cured [TEC, Ag filled] *†
3. Epotek - 410E [TEC, Ag filled]
4. Tra-Con - Tra-Duct 2902 [TEC, Ag filled] §

5. AI Technologies - 7609 film [TC, diamond filled] §†
6. Emmerson & Cummings (A Grace Co.) - Stycast 2850FT [TC, Al_2O_3 filled]
7. Masterbond - EP21ANHT [TC, AlN filled] *
8. Tra-Con - Tra-Bond BB 2151 [TC, Al_2O_3? filled]

9. Ciba Geigy - Araldite AW 106 [TI, not filled]
10. Devcon - 5 minute epoxy [TI, not filled]
11. Shell - Epon 815 + Versamid40 (2:1) [TI, not filled]

Greases:
1. Emmerson & Cummings (A Grace Co.) - Eccoshield SO [TEC, Ag filled]§
2. Emmerson & Cummings (A Grace Co.) - Eccobond 59C uncured [TEC, Ag filled]*†
3. Wakefield - 120 [TC, Zinc Oxide filled]§

§ Removable
* Thick paste
† Elevated temperature cure

4.0 Measurement Method

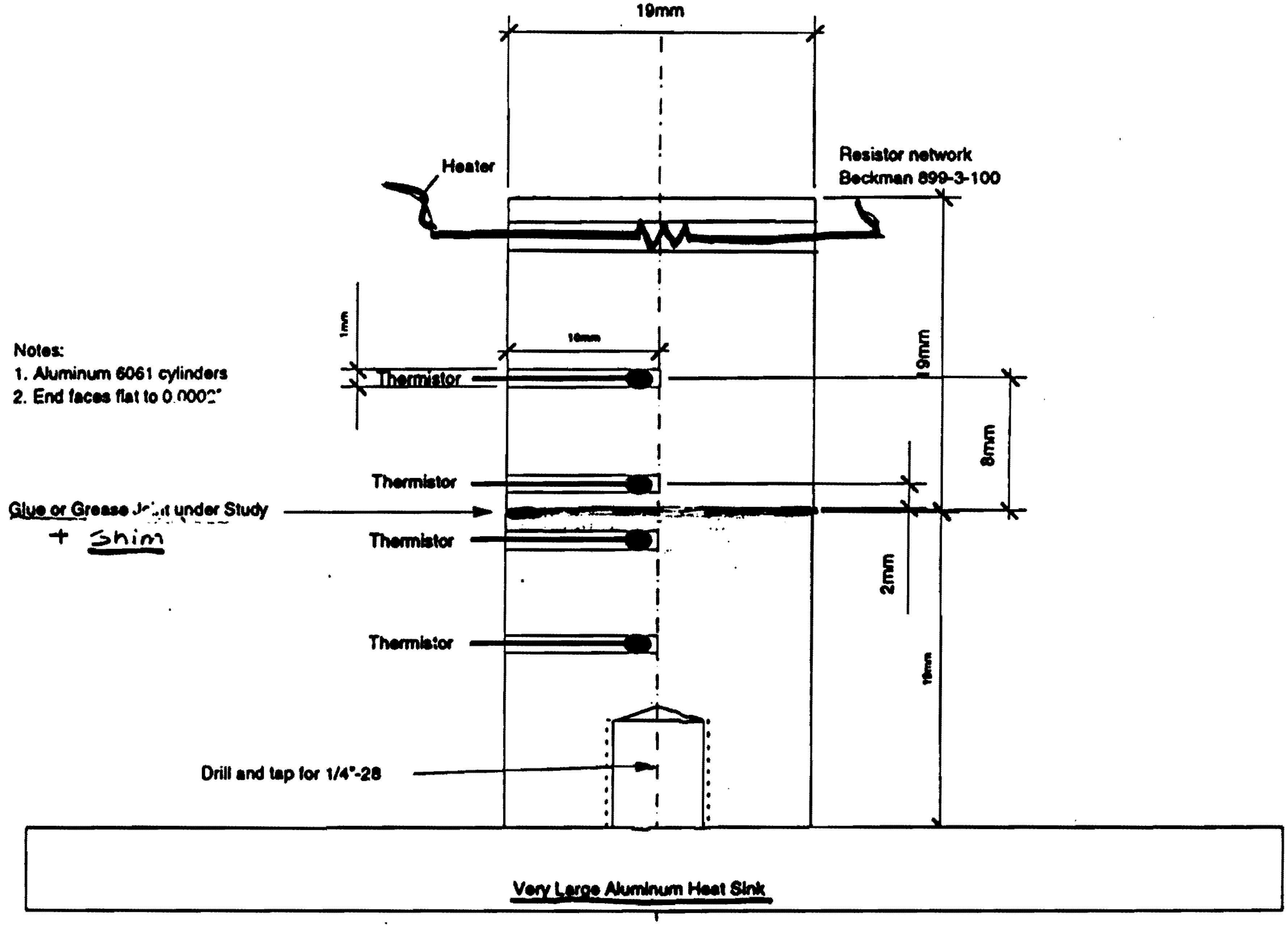
Figure 1 shows the test samples. They are made from two aluminum T6061 cylinders of 0.75" (19.0 mm) diameter and 0.75" (19.0 mm) length joined end to end with the product in question. For each product tested several samples were made. Joint thicknesses are: one "thin" sample (cylinders were pressed together tightly), and one each of 0.003", 0.006", and 0.009" shims. Three small shims are arranged 120° apart. Each shim is made of 0.003" kapton tape cut into thin triangles. To assemble the samples, shims are placed on the lower cylinder, the adhesive is applied as a dot in the middle of the sample cross-section, the upper cylinder is placed on top, and finally a 75g mass is set on top of the samples during the cure.

A 50 ohm resistor is inserted into a cross-drilled hole in the top of one cylinder and the other cylinder is screwed down to a large aluminum heat sink (12" x 12" x 1"). 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 centerline of the cylinder to measure an average cross-section temperature. Thermistors are used to monitor temperature because of their accuracy (6% change per degree C), quick response time, and small size (1 mm diameter).

From these four temperature readings, a plot of temperature versus axial distance is used to compare the thermal resistance of both the aluminum and the adhesive. Figure 2 is a sample of test data. The temperature difference from one thermistor is shown for both the aluminum region and the joint region. The slope of the line in the joint region is much higher because the thermal resistance of the joint material is much less than that of the aluminum. The resistance (in equivalent length of aluminum) across the aluminum is simply the axial distance between thermistor (for example, A-B or C-D). The resistance across the adhesive (in equivalent length of aluminum) is read by extrapolating the slope on one half of the sample back to the other half of the cylinder; the horizontal distance between them is the equivalent aluminum length required to achieve the same temperature rise as that across the adhesive plus the small portion of aluminum near the joint. The exact temperature difference across the gapis determined in a similar fashion, but the temperature rise in the small portion of aluminum near the joint should be subtracted off.

The results of this test are expressed in two more ways. The first method, "joint resistance" is calculated by dividing the temperature difference across the gap by the power density input to the resistor; this measure is appropriate for thin bonds ("thin" samples, as mentioned above) where the thickness is difficult to determine, e.g. when using a compound of low viscosity and no shims. It is a useful number to predict performance of such joints. We have found in all cases good proportionality of the thermal resistance to bond thickness. Surface effects were not found to be important. Using the second method, bulk thermal conductivity of the adhesive is calculated per equation 1 using known T_1, T_2, Q, x, and A.

In addition the integrity of the test configuration can be checked by back calculating the conductivity of the aluminum using power input, measured dimensions, and temperature.



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

Aluminum Cylinders,
Used to Measure Thermal Conductivity of Epoxy or Grease

Hans Jöstlein 10/21/93

Figure 1. Test Samples

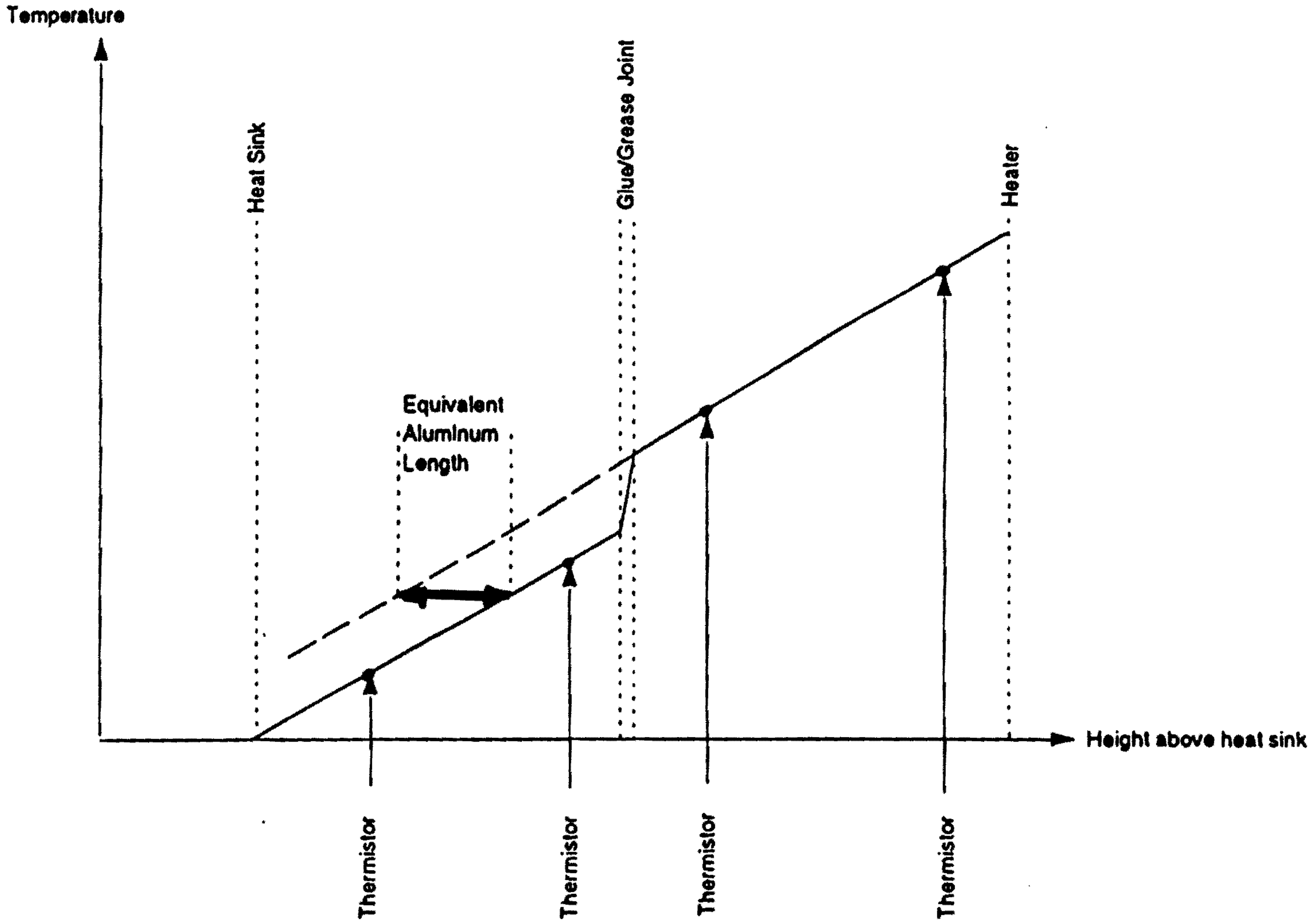


Figure 2. Plot of Temperature versus Axial Distance

Analysis: The four Thermisrtors yield directly the "equivalent aluminum length", which is that length of aluminum that has the same thermal resistance as the glue/grease joint under study.

The thermal conductivity of the aluminum used is determined from the measured electric heat input and the thermal gradient, which is measured twice.

This redundant measurement provides also a check on external heat loss.

5.0 Calibration

All thermistors were inserted into an insulated isothermal aluminum block, which was slowly heated from approximately $0^\circ C$ to $30^\circ C$, while their output was recorded. Three LM342 temperature converter IC's were recorded at the same time and cross-checked against a mercury thermometer. The log of the thermistor response was fit to a third order polynomial, to an accuracy of about $0.01^\circ C$. The IC's track each other very well. The calibration record is shown in Figure 3.

6.0 Data

In addition to joint equivalent aluminum length, aluminum conductivity, joint resistance, and bulk thermal conductivity, the electrical resistance and capacitance were also measured. In some cases, adhesives which are electrically insulating have an electrical resistance value recorded; this probably occurs from local contact between cylinders which are not completely flat. Cure schedule,, bond thickness, and date of fabrication are also noted. The cure schedule listed is the best possible one for that thermal compound - if a particular sample was made with another cure schedule, that is noted in the "type" column. Test data is shown in Tables 1 through 4. Table 1 shows results for electrically and thermally conducting adhesives; Table 2 shows results for thermally conducting adhesives; Table 3 shows results for thermally insulating adhesives; Table 4 shows results for all greases.

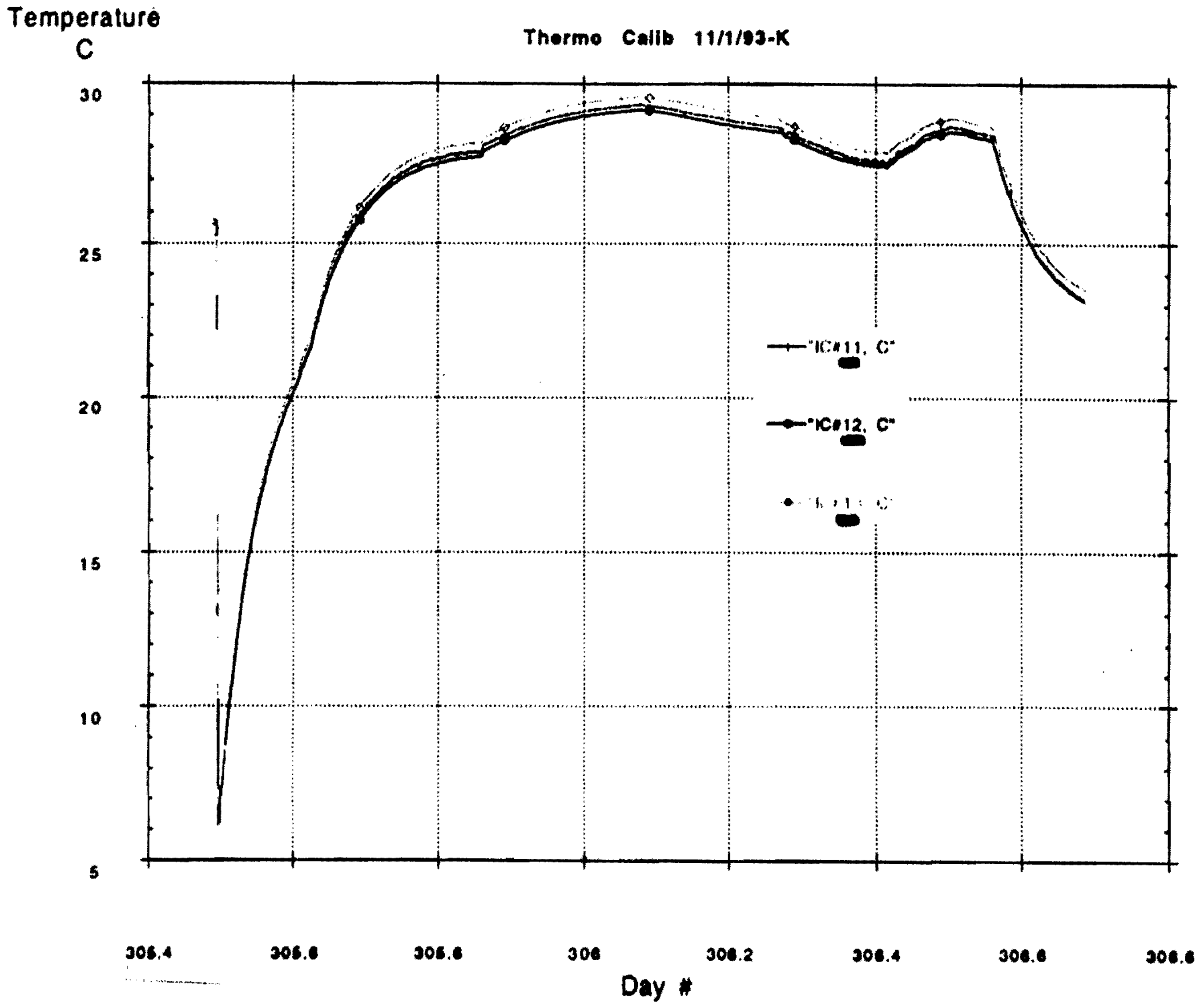


Figure 3. Calibration Record

Table 1. Thermally and Electrically Conductive Epoxies

Sample number	Run #	Mfgr.	Type	Filler	Best Cure Schedule	Bond Thickness [inch]	Date Sample Made	Date of Meast.	Power Density [W/cm^2]	L equiv Alum [cm]	Alum. Cond [W/m C]	Joint Resistance [C cm^2/W]	Bulk k [W/m C]	Elect. Res. [Ohm]†	Capacity [pF]
33	123	Tra-Con	Tra-Duct 2902	Ag	room temp	0.006	12/21/93	1/5/94	1.650	2.68	2.34	1.15	1.33	0.1	--
58	135	Tra-Con	Tra-Duct 2902	Ag	room temp	thin	1/6/94	1/25/94	0.702	1.32	246	0.54	--		--
59	136	Tra-Con	Tra-Duct 2902	Ag	room temp	0.003	1/6/94	1/25/94	0.704	1.97	270	0.73	1.04		--
60	137	Tra-Con	Tra-Duct 2902	Ag	room temp	0.006	1/6/94	1/25/94	0.899	3.75	237	1.58	0.96		--
61	138	Tra-Con	Tra-Duct 2902	Ag	room temp	0.009	1/6/94	1/25/94	0.700	6.30	241	2.62	0.87		--
3	122	Tra-Con	Tra-Duct 2902	Ag	room temp	0.003	12/21/93	1/5/94	0.500	1.23	228	0.54	1.41	0.1	--
Average													1.12		
31	101	Epotek	410E	Ag	room temp	very thin	12/8/93	12/6/93	0.385	0.60	185	0.32	--	c	--
44	105	Epotek	410E	Ag	room temp	0.003	12/8/93	12/6/93	0.433	1.61	205	0.78	0.96	0.8	--
43	104	Epotek	410E	Ag	room temp	0.009	12/8/93	12/6/93	0.713	4.20	182	2.81	0.81	0.7	--
	115	Epotek	410E	Ag	room temp	thin	12/8/93	1/4/94	0.780	0.28	128	0.22	--	0 3	--
54	131	Epotek	410E	Ag	room temp	thin	1/6/94	1/24/94	0.851	1.23	231	0.53	--	c	--
56	133	Epotek	410E	Ag	room temp	0.006	1/6/94	1/25/94	0.701	4.20	257	1.64	0.93	c	--
57	134	Epotek	410E	Ag	room temp	0.009	1/6/94	1/25/94	0.702	5.13	249	2.08	1.11	c	--
Average													0.96		
50	128	Chomerics (Grace)	Cho-Bond 584	Ag	room temp	thin	1/6/94	1/24/94	0.620	1.84	258	0.63	--	c	--
52	129	Chomerics (Grace)	Cho-Bond 584	Ag	room temp	0.006	1/6/94	1/24/94	0.582	3.93	255	1.54	0.99	c	--
53	130	Chomerics (Grace)	Cho-Bond 584	Ag	room temp	0.009	1/6/94	1/24/94	0.579	7.21	279	2.59	0.88	c	--
51	139	Chomerics (Grace)	Cho-Bond 584	Ag	room temp	0.003	1/6/94	1/24/94	0.707	2.20	238	0.92	0.83	c	--
51	140	Chomerics (Grace)	Cho-Bond 584	Ag	room temp	0.003	1/6/94	1/24/94	0.698	2.21	258	0.86	0.89	c	--
Average													0.90		
1.1	19	E&C (Grace)	Eccobond 59C-cured	Ag	6 hrs @ 150 C	0.0031	11/17/93	11/18/93	0.304	2.81	198	1.43	0.55	c	--
1.2	31	E&C (Grace)	Eccobond 59C-cured-5 days old	Ag	6 hrs @ 150 C	0.0031	11/17/93	11/23/93	0.156	2.80		1.42	0.55	c	--
2.1	22	E&C (Grace)	Eccobond 59C-cured	Ag	6 hrs @ 150 C	0.0088	11/17/93	11/19/93	0.304	4.03		1.91	0.88	c	--
2.1	23	E&C (Grace)	Eccobond 59C-cured	Ag	6 hrs @ 150 C	0.0066	11/17/93	11/19/93	0.524	4.02		1.91	0.88	c	--
Average													0.72		

Notes: † c = conductive, ∞ = non-conductive

Table 2. Thermally Conductive Epoxies

Sample number	Run #	Mfgr.	Type	Filler	Best Cure Schedule	Bond Thickness [inch]	Date Sample Made	Date of Meast.	Power Density [W/cm^2]	L equiv Alum [cm]	Alum. Cond [W/m C]	Joint Resistance [C cm^2/W]	Bulk k [W/m C]	Elect. Res. [Ohm]†	Capacity [pF]
10	116	Tra-Con	Tra-Bond BB2151	?	room temp	0.0090	12/13/93	1/4/94	0.540	5.20	199	2.61	0.88	∞	54
42	117	Tra-Con	Tra-Bond BB2151	?	room temp	0.0090	12/13/93	1/4/94	0.580	5.20	214	2.41	0.95	∞	59
41	118	Tra-Con	Tra-Bond BB2151	?	room temp	0.0090	12/13/93	1/4/94	0.770	5.40	211	2.56	0.89	∞	55
9	119	Tra-Con	Tra-Bond BB2151	?	room temp	0.0090	12/13/93	1/4/94	0.620	5.66	209	2.71	0.84	∞	52
2	120	Tra-Con	Tra-Bond BB2151	?	room temp	0.0030	12/13/93	1/4/94	0.640	2.63	216	1.21	0.63	∞	126
1	121	Tra-Con	Tra-Bond BB2151	?	room temp	thin	12/13/93	1/4/94	0.420	1.38	217	0.63		0.2	
Average													0.84		
30	106	E&C (Grace)	Stycast 2850FT	Al2O3	room temp	thin	12/13/93	12/14/93	0.780	1.74	260	0.67		∞	245
32	107	E&C (Grace)	Stycast 2850FT	Al2O3	room temp	0.0030	12/13/93	12/14/93	0.640	3.21	223	1.44	0.53	∞	110
33	106	E&C (Grace)	Stycast 2850FT	Al2O3	room temp	0.0090	12/13/93	12/14/93	0.780	7.67	225	3.42	0.67	∞	
Average													0.60		
12a/21b	37	Masterbond	EP21ANHT,cured 80 C x 10 hr	AlN	room temp	0.0069	12/1/93	12/2/93	0.754	6.38	233	2.74	0.84	∞	
13	38	Masterbond	EP21ANHT,cured 80 C x 10 hr	AlN	room temp	0.0093	12/1/93	12/2/93	0.400	8.33	216	3.86	0.61	∞	113
23	?	Masterbond	EP21ANHT,cured 80 C x 10 hr	AlN	room temp	0.0630	12/1/93	12/2/93	0.701	69.00	290	24	0.67	∞	7
23	38	Masterbond	EP21ANHT,cured 80 C x 10 hr	AlN	room temp	0.0630	12/1/93	12/2/93	0.254	63.40	255	24.5	0.65	∞	
Average													0.64		
9a/10b	24	Al Tech	7609	Diamond	20 min @ 60 C	0.0030	11/18/93	11/23/93	0.507	3.38	--	1.48	0.51	∞	
42	102	Al Tech	7609	Diamond	20 min @ 60 C	0.0090	12/8/93	12/9/93	0.689	5.60	210	2.7	0.85	∞	
Average													0.68		

Notes: † c = conductive, ∞ = non-conductive

Table 3. Thermally Insulating Epoxies

Sample number	Run #	Mfgr.	Type	Filler	Best Cure Schedule	Bond Thickness [inch]	Date Sample Made	Date of Meast.	Power Density [W/cm^2]	L equiv Alum [cm]	Alum. Cond [W/m C]	Joint Resistance [C cm^2/W]	Bulk k [W/m C]	Elect. Res. [Ohm]†	Capacity [pF]
34	109	Shell	Epon 815 /Versamid 40, 2:1	Not filled	room temp	thin	12/13/93	12/14/93	0.750	0.65	204	0.32	--	nc	
35	110	Shell	Epon 815 /Versamid 40, 2:1	Not filled	room temp	0.003	12/13/93	12/14/93	0.690	8.86	226	3.89	0.20	nc	
36	111	Shell	Epon 815 /Versamid 40, 2:1	Not filled	room temp	0.009	12/13/93	12/14/93	0.870	24.04	232	10.39	0.22	nc	
Average													0.21		
37	112	Ciba-Geigy	Araldite AW 106	Not filled	room temp	thin	12/13/93	12/14/93	0.680	1.29	222	0.56	--	nc	
39	113	Ciba-Geigy	Araldite AW 106	Not filled	room temp	0.003	12/13/93	12/14/93	0.850	7.92	222	3.55	0.21	nc	
40	114	Ciba-Geigy	Araldite AW 106	Not filled	room temp	0.009	12/13/93	12/14/93	0.680	22.70	253	8.96	0.26	nc	
Average													0.24		
12.1	11	Devcon	5 min epoxy	Not filled	room temp	thin	11/17/93	11/17/93	1.635	3.57	208	1.71	--	nc	
12.1	12	Devcon	5 min epoxy	Not filled	room temp	thin	11/17/93	11/17/93	3.712	3.66	194	1.9	--	nc	
Average													--		

Notes: † c = conductive, nc = non-conductive

Table 4. Greases

Sample number	Run #	Mfgr.	Type	Filler	Best Cure Schedule	Bond Thickness [inch]	Date Sample Made	Date of Meast.	Power Density [W/cm^2]	L equiv Alum [cm]	Alum. Cond [W/m C]	Joint Resistance [C cm^2/W]	Bulk k [W/m C]	Elect. Res. [Ohm]†	Capacity [pF]
24.1	8	Wakefield	120-2 w/ 0.5 kg wt	Zinc Oxide	n/a	-	11/10/93	11/10/93	0.446	0.63	193	0.33		nc	--
24.1	9	Wakefield	120-2 w/ 0.5 kg wt	Zinc Oxide	n/a	-	11/10/93	11/10/93	2.398	0.62	189	0.33		nc	--
24.2	10	Wakefield	120-2 w/ 0.5 kg wt, 7 days old	Zinc Oxide	n/a	-	11/10/93	11/17/93	1.583	0.36	193	0.19		nc	--
24.4		Wakefield	120-2	Zinc Oxide	n/a	0.0070	12/2/93	12/2/93	0.844	8.50	205	3.16	0.56	nc	--
24.5		Wakefield	120-2	Zinc Oxide	n/a	0.0200	12/2/93	12/2/93	1.004	13.10	218	6.01	0.85	nc	--
24.6	100	Wakefield	120-2,7 days old	Zinc Oxide	n/a	0.0200	12/2/93	12/9/93	0.640	11.70	206	5.69	0.89	nc	--
Average													0.73		
3.4	27	E&C (Grace)	Eccoshield SO	Ag	n/a	starved	11/23/93	11/23/93	0.505	2.26		1.02		c	--
3.5	28	E&C (Grace)	Eccoshield SO,shim, not pressed	Ag	n/a	0.002	11/23/93	11/23/93	0.157	1.65		0.78	0.65	c	--
3.6	29	E&C (Grace)	Eccoshield SO,shim, clamped	Ag	n/a	0.002	11/23/93	11/23/93	0.156	1.40		0.69	0.74	c	--
Average													0.89		
3.1	13	E&C (Grace)	Eccobond 59C-uncured1kg wt	Ag	n/a	0.0024	11/17/93	11/17/93	0.734	3.79	239	1.59	0.38	c	--
3.1	14	E&C (Grace)	Eccobond 59C-uncured1kg wt	Ag	n/a	0.0024	11/17/93	11/17/93	0.432	3.63	235	1.55	0.39	c	--
3.3	15	E&C (Grace)	Eccobond 59C-uncured, 1kg wt	Ag	n/a	0.0024	11/17/93	11/18/93	1.253	2.90	240	1.21	0.50	c	--
3.3	16	E&C (Grace)	Eccobond 59C-uncured, 1kg wt	Ag	n/a	0.0024	11/17/93	11/18/93	0.212	2.85	228	1.25	0.49	c	--
Average													0.44		
	1	Dry Joint	cleaned with alcohol	Not filled	n/a	thin	11/5/93	11/5/93	0.550	3.35	218	1.54			
	2	Dry Joint	cleaned with alcohol	Not filled	n/a	thin	11/5/93	11/5/93	1.827	3.30	210	1.58			
	3	Dry Joint	cleaned with alcohol	Not filled	n/a	thin	11/5/93	11/5/93	0.133	3.18	228	1.41			
	4	Dry Joint	with fingerprint	Not filled	n/a	thin	11/8/93	11/8/93	1.685	2.44	189	1.29			
	5	Dry Joint	with fingerprint	Not filled	n/a	thin	11/8/93	11/8/93	1.690	2.29	188	1.21			
	6	Dry Joint	with fingerprint	Not filled	n/a	thin	11/10/93	11/10/93	0.446	2.50	194	1.29			
	7	Dry Joint	cleaned with alcohol	Not filled	n/a	thin	11/10/93	11/10/93	0.446	4.08	220	1.84			

Notes: † c = conductive, nc = non-conductive

7.0 Conclusions

A summary of the measurements is given in Table 5. For each product tested the joint resistance shows good correlation to joint thickness. The precision of the conductivity measurement is porbably best for the thickest samples because as joint thickness increases, bond thickness measurement error as a percentage decreases. In addition, the aluminum cylinders were flat to only approximately 0.001" which may have caused problems on thinner samples. Several samples were tested after some aging transpired and no noticable change in performance was observed.

Table 5. Summary of Thermal Conductivity Measurements

	Thermal Conductivity Range: "k" [W/m°C]	Minimum Joint Resistance [°C cm^2/W]
TEC	0.5 (Eccobond 59C) - 1.4 (Tracon 2902)	0.2 (Epotek 410E)
TC	0.5 (Stycast 2850) - 1.0 (Tracon BB2151)	0.6 (Stycast 2850, Tracon BB2151)
TI	0.2 (Epon 815) - 0.3 (Araldite AW 106)	0.3 (Epon 815)
Grease	-	0.2 (Wakefield 120)

Of the thermally and electrically conductive adhesives, the product with the highest thermal conductivity (1.4 W/m°C) is Tracon 2902; its joint resistance is a minimum at 0.5°C cm^2/W. It is spreadable with little resistance when applied within approximately three minutes of mixing and removable with proper fixturing. The next best performer is Epotek 410E with a measured thermal conductivity of 0.9 W/m°C and minimum joint resistance of 0.2 C cm^2/W.

Of the thermally conductive adhesives, the product with the highest thermal conductivity (approximately 1.0 W/m°C) is Tracon BB2151; its joint resistance is a minimum at 0.6°Ccm^2/W. It has not yet been tested for removability. The next best performer is Stycast 2850 FT with a measured thermal conductivity of 0.6 W/m°C and minimum joint resistance of 0.7 C cm^2/W.

Of the thermally insulating adhesives, the measured thermal conductivity of both Shell Epon 815/Versamid 40and Araldite AW 106 was approximately 0.2-0.3 W/m°C; the minimum joint resistance of Shell Epon 815/Versamid 40 (0.3°C cm^2/W) was slightly lower than that of the Araldite AW 106 (0.6°C cm^2/W). Both are easy to spread, but not removable.

Of the greases, the product with the highest thermal conductivity (0.9 W/m°C) is Wakefield 120; its joint resistance is a minimum at 0.3°C cm^2/W. It is spreadable with little resistance when applied within approximately three minutes of mixing and removable with proper fixturing. The next best performer is Eccoshield SO with a measured thermal conductivity of 0.7 W/m°C and minimum joint resistance of 0.7 C cm^2/W. A dry joint was also measured and, as expected, better results can be obtained with the use of a thermal compound.

8.0 Future Work

The measurements presented in this paper help to discern what type of thermal performance can be expected from different types of joint materials. The design of individual joints, the materials which are joined, and the fixturing process used in assembly are also part of making a reliably low resistance thermal joint. These topics will be addressed in future D0 Engineering Notes.

9.0 References

[1] W. Cooper, private communication.

Appendix A - Error Analysis

Equation A.1 describes the energy balance applicable to these measurements. Values for this test method are reported here and calculated in the following energy balance.

$Q_{in} = (Q_{cond,\ sample} + Q_{cond,\ instrumentation}) + Q_{convection}$ Eqn. A.1

where: Q_{in} =power to 50 ohm resistor
$Q_{cond,\ sample}$ = heat conducted along sample axis
$Q_{cond,\ instrumentation}$ = heat conducted along instrumentation wires
$Q_{convection}$ = heat convected to surrounding air

In these tests, the power input to the resistor imbedded in the aluminum cylinder was:

$Q_{in} = 1.7 - 4.5$ W

Q_{in} / Area = 5996 - 15,870 $W/m^2$1 (for a cylinder area of 0.000284 m^2)
==> {0.70 - 1.8x power density of 1 chip => single sided}
==> {0.35 - 0.9x power density of 2 chips => double sided}

The heat through the instrumentation leads is given by:
$Q_{cond,\ instrumentation} = Q_{cond,\ power\ leads} + Q_{cond,\ thermistors}$
$= 0.041 + 0.017$ W $= 0.058$ W
$\approx 3\%$ of 1.7W

Heat conducted away is given by:
$Q_{convection} = hA_{surface}(T_{surface} - T_{air})$
$= .011$ W
$\approx < 6\%$ of 1.7 W
where: h = convection coefficient [W/m^2 °C]
$A_{surface}$ = surface area of cylinder [m^2]
$T_{surface}$ = surface temperature of cylinder [°C]
T_{air} = air temperature [°C]

In this calculation the entire surface of the cylinder was assumed to be at 30°C. Actually, the hottest temperature were closer to 27-28°C and the entire surface was not at this temperature, it approaches room temperature near the heat sink.

The heat conducted through the sample is given by:
$Q_{cond,\ sample} = kA(T_1 - T_2)/x$

There are three places which have potential for error. The first is the cross-sectional area. The diameter is assumed to vary ±0.005" from the nominal 0.75' and the shims take up roughly 3.5% of the area for a total of less than 4% reduction in area. A second source of error exists in the measurement of the joint thickness. The smallest joint is only 0.003" thick, so a 0.0005" imperfection in shim height results in a 17% error. A third source of error exists in the thermistor spacing measurement. The thermistor spacing used to determine aluminum conductivity is from center to center of the drilled holes. If the thermistors contact the side wall of the drilled hole, the spacing should be altered by one-half of the hole diameter. This has potential to affect the aluminum thermal conductivity calculation by 16%. The published value for thermal conductivity of T6061 aluminum is 172 W/m°C and 16% of that is or 27 W/m°C.

1. INSTRUMENTATION
    - Power Supply
    - Thermistors
        - at center of sample
        - individually calibrated
        - fast response ≈ seconds
2. SYSTEM
    - Runs at 22 - 30 °C
    - Radiation is negligible
    - No insulation, all temps rise steadily ≈1mV/min.
3. ADHESIVES
    - All samples mixed per manufacturers instructions
    - Minimum 3 min. mixing time
    - Curing verified via mixing containers
        - All samples cured except EpoTek 410E
            - too much hardener? evaporates?
            - scale reading decreases while weighing
    - Application of adhesive satisfactory
4. TEST SAMPLES
    - Aluminum cylinders
        - specified flat to 0.0002"
        - "dimples" 1-3 mils tall
        - ø 0.75" ±0.005" ≈ 3% area
    - Adhesive thickness
        - shims determine thickness
        - good consistency of k in 3, 6, 9 mil samples
        - samples measured on CMM, continuing # crunching