D0 ENGINEERING NOTE

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D0 SILICON UPGRADE

THERMALLY INDUCED STRESSES IN THE
COMPONENTS OF A D0 LADDER IN THE SILICON
TRACKER

July 2, 1996

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**Thermally Induced Stresses in the Components
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During the operation of the silicon tracker, the ladders will be in direct thermal contact with a cooling channel. The expected operating temperature of the cooling channel is 0°C, maintained by a cooling fluid whose bulk temperature is below 0°C. The assembly temperature is assumed to be 22°C.

Due to the mis-match of material expansion coefficients, thermal stresses will be induced in the epoxy, beryllium, and silicon of the ladders. Calculations are presented here as well as some thermal cycling results on test samples. Shown in Figures 1 and 2 are perspective views of the top and bottom of a 3 chip ladder.

The silicon temperature within the ladders will not be uniform due to the relative location of the heat dissipating components and the cooling channel. As an example the following plot demonstrates the expected temperature distribution in the 3 chip single sided ladder during operation. Under expected operating conditions of 0.75 W hybrid component power dissipation and 0.5 W per SVX II chip, the temperature profile is shown for two situations of how the ladder is constructed.*

The cooling channel corresponds roughly to locations on the silicon between 32 and 42 mm. The silicon in this region is sandwiched between two plates of beryllium and is about 4°C. For a construction temperature of 22°C the beryllium/silicon/beryllium assembly will see a 18°C change in temperature. To be conservative a 20°C temperature change will be assumed (some larger temperature extremes will be considered) within the ladder.

* The plot is taken from Reference 1 where more detailed discussion of the cooling and power dissipation of the ladder components is shown. The plot is shown here as a means of indicating the potential temperature differences which may be experienced on a ladder between the construction temperature of ~22°C and the operating temperature.

Figure 3

The material properties of the ladder components, with references, are shown in Table 1.

Material	Property	value	Source of information
beryllium	alpha (ppm/°C)	11.4	"Designing With Beryllium", a pamphlet published by Brush-Wellman Inc.
beryllium	E (E9 Pa)	303.4	"Designing With Beryllium", a pamphlet published by Brush-Wellman Inc.
epoxy (DGEBA/TETA based)	alpha (ppm/°C)	59	Specification sheet for Hexcel 5313 epoxy.
epoxy (DGEBA/TETA based)	alpha (ppm/°C)	60-70	Handbook of Epoxy Resins, by Lee and Neville, McGraw-Hill, 1967, pp. 17-16 and 14-24/25
epoxy (DGEBA/TETA based)	E (E9 Pa)	1.59	Handbook of Epoxy Resins, by Lee and Neville, McGraw-Hill, 1967, pp. 13-7
silicon	alpha (ppm/°C)	2.6	Handbook of Semiconductor Silicon Technology, O'Mara, Herring, and Hunt, Noyes Publications, 1990, P. 431
silicon	E (E9 Pa)	131	Handbook of Semiconductor Silicon Technology, O'Mara, Herring, and Hunt, Noyes Publications, 1990, P. 424

Table 1

The material thicknesses play an important role in determining the stresses at the operating temperature. The 3 chip ladder is designed with 0.300 mm thickness beryllium substrates and 0.075 mm thickness glue joints. The silicon thickness is 0.300 mm.

The 6 chip (3 chip double sided) and 9 chip (5 chip wide double sided) substrate thicknesses have yet to be determined. Candidate thicknesses are between 0.300 and 0.700 mm and will be based primarily on the trade-off between cooling performance and the mass penalty of the thicker beryllium. 0.300, 0.500, and 0.700 mm thicknesses will be considered.

The calculation of the stresses in the ladder may be simplified, as in Figure 4, by assuming an arbitrary length piece which is uniformly cooled from room temperature. The component stresses are calculated in the following way. Assembly is at room temperature, at which point all components are in a stress-free state. This is achieved by using a room temperature cure epoxy. Upon cooling, the various materials will all contract to the same point if no de-lamination of the adhesive or breaking of material occurs, and if there is no out-of-plane bow of the piece. Again, since the stresses are local, the model for calculation is greatly simplified by taking the piece shown in Figure 4 through a uniform temperature change.

The amount of stress at the equilibrium point is determined by first assuming that all materials contract as if unconstrained on one end. The force required to balance the components back to the equilibrium point is then calculated. See Figure 4.

Figure 4

Figure 5

The epoxy stresses induced in the thin glue joint are not significantly affected by varying the beryllium thickness. The beryllium, with a far dominant elastic modulus and large cross-sectional area, largely dictates the final length of the piece and the silicon stress is determined by this final length.

The shear strength of Hexcel 5313 is 3000 psi [2]. However, experience has shown that shear strength of a thin glue joint is highly subject to variation. Inadequate mixing, poor control in measuring the resin and hardener amounts, and grease or dirt on the part surfaces can substantially decrease adhesion strength. With approximately 230 psi shear stress in the glue joint there is an indication that the adhesive stresses will be well below dangerous levels. Good quality control during ladder construction should result in adequate adhesive strengths during the silicon detector operation.

Using the same method outlined above, stress in the beryllium and silicon ladder components is calculated. Only the silicon stresses will be discussed here since the resulting beryllium stresses are not significant (they were 1265, 817, and 604 psi for 0.300, 0.500, and 0.700 mm thickness beryllium at $dT = -20^{\circ}\text{C}$).

Figure 6

The silicon stress is not highly variable with the variation in the beryllium substrate thickness. However, stresses around 3000 psi will be experienced in the silicon detectors during operation of the ladder. Given the sensitivity of silicon detectors to surface damage, it is unclear what this compressive stress on the silicon will do regarding the performance of the detector during operation.

Test Structures

Test structures were constructed of aluminum, epoxy, and silicon in order to cycle the epoxy joints through stresses greater than those [in the epoxy] during ladder operation. 1" by 1" squares of aluminum were glued to the top and bottom surfaces of 1" by 1" silicon using Hexcel 5313 epoxy. The aluminum thickness was 0.3 mm. Using typical modulus and expansion coefficients for aluminum (69 GPa modulus and 23 ppm/°C expansion coefficient) the epoxy stress values are calculated, in the same way as described above, for the test structures through a theoretical temperature change of -40°C.

As shown in Figure 7, the expected epoxy stress is roughly 220 psi. This corresponds to a temperature change for our test samples of -21°C, which occurs at 1°C for an assembly temperature of 22°C.

Figure 7

The epoxy stresses were calculated by Bob Wands of the Analysis Group on 11W of Fermilab, using ANSYS. Using beryllium thicknesses of 0.300 mm and cooling the structure through a 20°C change in temperature, ANSYS predicts 1327, 231, and 2770 psi stresses for the beryllium, epoxy, and silicon, respectively. These numbers compare to the method outlined above where corresponding stresses of 1265, 232, and 2646 psi were calculated. The ANSYS numbers just presented are taken from the solution well away from the edge, so end effects and those of the constraints were minimized for these numbers reported.

To understand the end effects the element size was reduced near the end of the piece. The following plots show the stresses along the longitudinal axis of the parts (labeled sx at the table bottom) and the stress intensity. For these 6 plots, the majority of the stresses are as reported above. For instance, the stress intensity for beryllium is 9154 which is units of kPascals. This converts (by a factor of 6895) to 1327 psi, as reported above.

The beryllium stress intensity decreases monotonically near the edge of the glue joint. The epoxy, on the other hand, increases from its stress of 1593 kPa over the majority of the joint to a peak value of 3140 kPa, or 455 psi. The stress in the glue joint near the end of the piece is approximately twice as high near the edge as over the majority of the glue joint. This level of stress intensity, although not theoretically higher than the shear strength of epoxy, could present problems of delamination in this region of the ladder and must be further studied.

The majority of the stress intensity in the silicon is 19100 kPa, or 2770 psi. The silicon stress intensity decreases sharply to 9970 kPa near the end, then jumps abruptly to 23920 kPa (3470 psi) at the joint edge.

Conclusions and evaluation

The epoxy, beryllium, and silicon experience significant amounts of stress upon cool-down of the structure. The beryllium and silicon stresses are well below those which risk physically cracking or breaking the pieces, however given the known sensitivity of silicon detectors to damage, the stresses of ~3500 psi may be cause for concern.

The stresses induced in the epoxy during cool-down do not approach the reported maximum shear stress of the epoxy. The ANSYS predicted stresses near the end of the piece are approximately 450 psi and is sufficient stress to cause concern. These adhesive joints may fail in one of two ways:

1. Delamination of the glue joint occurs when the epoxy does not sufficiently adhere to the surface of the adherends. Good quality control will ensure that the parts are properly and adequately cleaned of grease and dirt to ensure sufficient adhesion is obtained in all glue joints at the material interfaces.
2. Shear failure occurs in the epoxy itself fails. The published shear strengths of epoxies are well above 1000 psi (3000 psi for Excel 5313 resin). The maximum shear stress in the epoxy, under a temperature change of -20°C, is 455 psi. Low shear stress failure is an indication of poorly mixed epoxy. A full epoxy mixing procedure has been written for ladder construction where, if followed, will result in properly mixed epoxy where no shear failures occur.

The simple conclusion is that good cleaning and thorough mixing of the epoxy should result in no adhesive failures of the ladder components. Proper quality control during ladder construction will eliminate these uncertainties and result in good ladders being constructed each and every time.

1. Ratzmann, P. M., Thermal Analysis of the D0 3 Chip Single Sided Ladder, May/1996 to be submitted as a D0EN.
2. Hexcel technical data sheet indicates ASTM D-1002 as the test method.

ANSYS 5.1
JUN 20 1996
09:46:07
PLOT NO. 4
POST1
STEP=1
SUB =1
TIME=1
PATH PLOT
NOD1=242
NOD2=202

ZV =1
DIST=0.75
XF =0.5
YF =0.5
ZF =0.5

sx at be-si interface for epoxy

ANSYS 5.1
JUN 20 1996
09:46:03
PLOT NO. 2
POST1
STEP=1
SUB =1
TIME=1
PATH PLOT
NOD1=242
NOD2=202

sx at be-si interface for beryllium

ANSYS 5.1
JUN 20 1996
09:46:02
PLOT NO. 1
POST1
STEP=1
SUB =1
TIME=1
PATH PLOT
NOD1=242
NOD2=202

ZV =1
DIST=0.75
XF =0.5
YF =0.5
ZF =0.5

stress intensity at be-si interface for beryllium

ANSYS 5.1
JUN 20 1996
09:46:07
PLOT NO. 3
POST1
STEP=1
SUB =1
TIME=1
PATH PLOT
NOD1=242
NOD2=202

ZV = 1
DIST=0.75
XF = 0.5
YF = 0.5
ZF = 0.5

stress intensity at be-si interface for epoxy

ANSYS 5.1
JUN 20 1996
06:58:48
PLOT NO. 2
POST1
STEP=1
SUB =1
TIME=1
PATH PLOT
NOD1=12491
NOD2=12483

ZV =1
DIST=0.75
XF =0.5
YF =0.5
ZF =0.5
PRECISE HIDDEN

sx in si at spoxy interface

ANSYS 5.1
JUN 20 1996
06:58:12
PLOT NO. 1
POST1
STEP=1
SUB =1
TIME=1
PATH PLOT
NOD1=12491
NOD2=12483

ZV =1
DIST=0.75
XF =0.5
YF =0.5
ZF =0.5
PRECISE HIDDEN

stress intensity in si at epoxy interface