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Investigation of Compliant Layer in SuperGLAST CTE Mismatch Problem

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Abstract

Because of the large difference in coefficient of thermal expansion (CTE) between the lead converters and the silicon detectors in the SuperGLAST trays, failure levels are being predicted for the silicon detectors. This CTE mismatch is only further compounded by the substantial thickness of the lead converters required for the SuperGLAST trays. Solutions ranged from building lead/carbon composites, which lower the thermal growth of the lead converters, to some how decoupling the converters from the bias sheet through compliant adhesives. By replacing the epoxy adhesives used in bonding the converter layer to the kapton bias sheet with more compliant adhesives, the CTE interaction between the converters and the adjacent bias sheet would be reduced; thus, lowering the stress state in the silicon detectors to an acceptable level.

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GLAST

Revision Log

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Table of Contents

1. Definitions

α or CTE:	Coefficient of (linear) Thermal Expansion
GFRP:	Graphite Fiber Reinforced Plastic
E:	Modulus of Elasticity
G:	Shear Modulus
Pb:	Lead
W:	Tungsten
Si:	Silicon Detectors
RTV:	Room Temperature Vulcanizing Silicone Rubber
SLAC:	Stanford Linear Accelerator Center
1D:	One Dimensional
RL:	Radiation Length
C-C:	Carbon-Carbon
Psi:	pounds per square inch
Ksi:	1000 pounds per square inch, 1000 = (kilo)
Adherend:	a surface or substrate to which an adhesive adheres
Adherent:	a bonding agent (adhesive) which adheres to a surface or substrate

2. Introduction

Recent thermal testing of a prototype tray and ladder test fixture revealed a possible problem due to the CTE mismatch between the silicon and lead conversion layers. Initial hand calculations further show that the CTE mismatch problem was much more prominent in the Super GLAST tracker tray conversion layers than in the regular GLAST tracker trays. Several options were investigated to address this CTE mismatch, which included lead composites, compliant adhesives, and alternate converter materials. The idea of lead composites was addressed in technical note number HTN-102050-0011[2].

This technical document addresses the use of compliant adhesives and alternate converter materials in the SuperGLAST tracker trays, and compares them to the present baseline design.

3. Summary of SuperGLAST Baseline Design

The baseline design for SuperGLAST consists of a C-C tray closeout frame with a carbon honeycomb core. The core is sandwiched in the closeout frame between two sheets of GFRP. P75 fiber with a RS-11 cyanate ester resin matrix is present baseline being modeled for the GFRP face sheets. The payload for the tray consists of a 1.4 mm thick conversion layer of lead bonded to the bottom GFRP face sheet of each SuperGLAST tray. This converter thickness represents a 25% radiation length. A 0.118 mm thick kapton/copper bias sheet is bonded to the converter layer on one side and to the GFRP face sheet on the other side, and then 0.4mm thick silicon detector ladders are bonded to the bias sheets. Presently a 0.075mm adhesive bond line thickness is what has been used for baseline on GLAST prototype trays that have been built at SLAC.

4. Summary Compliant Adhesive Results

4.1 Assumptions

For the following study, four assumptions were made:

1.) The temperature gradient for CTE mismatch was set at the lower extreme of -30^{o}C, giving a ΔT from room temperature of -51^{o}C.

2.) The loading condition for the adhesive layer was considered 1D with no out-of-plane bending taking place.

3.) The stiffness of the adhesive was considered to be much less than either one of the adherends. (i.e. $E_{adhesive}$, $t_{adhesive}$ << $E_{adherend1}$, $t_{adherend1}$ & $E_{adherend2}$, $t_{adherend2}$)

4.) Symmetric boundary conditions were assumed at the mid-plane of the converter layer.

4.2 Material Properties for Adherends used in Adhesive Study: E, t, & a

Adherend Type	Elastic Modulus, E (GPa)	Thickness, t (mm)	Coefficient of Thermal Expansion, a (ppm/^{o}C)
GFRP face sheet	90	0.318	-0.088
SuperGLAST Lead Converter	13.8	1.4	29.3
SuperGLAST Tungsten Converter	386.1	0.875	4.5
Bias sheet	7.536	0.118	20.75
Silicon Detector	130	0.4	2.5

Table 1. Material Properties for Adherends: E, t, a

Note: Adherend, see definitions

4.3 Formulation

The basis for determining both the shear stress in the adhesive layer and the normal stresses in the two adherends comes from using the following three general equations for elasticity:

$$s_1 = E_1\left(\frac{\partial u_1}{\partial x} - a_1 \Delta T\right), \qquad (1)$$

$$s_2 = E_2(\frac{\partial u_2}{\partial x} - a_2 \Delta T)\,, \qquad (2)$$

$$t_3 = \frac{G_3}{t_3}(u_2 - u_1)\,, \qquad (3)$$

where,

σ_1 = normal stress in adherend 1

σ_2 = normal stress in adherend 2

τ_3 = shear stress in adhesive

And the following three equilibrium equations:

$$t_1 \frac{\partial s_1}{\partial x} + t = 0\,, \qquad (4)$$

$$t_2 \frac{\partial s_2}{\partial x} - t = 0\,, \qquad (5)$$

$$t_1 s_1 + t_2 s_2 = 0\,, \qquad (6)$$

The following expressions for displacements, u_1 and u_2 were derived:

$$u_1 = \frac{f}{c}\sinh(cx) + ax\,, \qquad (7)$$

$$u_2 = -\frac{g}{c}\sinh(cx) + ax\,, \qquad (8)$$

where

$$f = \frac{\Delta T}{\cosh(\frac{cL}{2})} \frac{t_2 E_2 (a_1 - a_2)}{t_1 E_1 + t_2 E_2}\,, \qquad (9)$$

$$g = \frac{\Delta T}{\cosh(\frac{cL}{2})} \frac{t_1 E_1 (a_1 - a_2)}{t_1 E_1 + t_2 E_2}\,, \qquad (10)$$

$$a = \Delta T \frac{a_1 t_1 E_1 + a_2 t_2 E_2}{t_1 E_1 + t_2 E_2}\,, \qquad (11)$$

$$c = \sqrt{\frac{G_3}{t_3} \frac{t_1 E_1 + t_2 E_2}{t_1 E_1 t_2 E_2}}\,, \qquad (12)$$

and $$-\frac{L}{2} \le x \le \frac{L}{2}, \quad L = Length_{Converter}$$

Substituting expressions (7) and (8) into equations (1), (2), and (3), the normal stresses for the two adherends and the shear stress for the adhesive can be expressed as a function of (x):

$$s_1(x) = E_1 E_2 \Delta T t_2 [\frac{a_2 - a_1}{t_1 E_1 + t_2 E_2}](1 - \frac{\cosh(cx)}{\cosh(\frac{cL}{2})}), \qquad (13)$$

$$s_2(x) = E_1 E_2 \Delta T t_1 [\frac{a_2 - a_1}{t_1 E_1 + t_2 E_2}](\frac{\cosh(cx)}{\cosh(\frac{cL}{2})} - 1), \qquad (14)$$

$$t_3(x) = \frac{G_3}{ct_3} \sinh(cx) \frac{\Delta T}{\cosh(\frac{cL}{2})} (a_2 - a_1), \qquad (15)$$

With the three stress states expressed as functions of (x), the adhesive bond thickness, adhesive shear modulus, and converter material were varied to determine the effect of the three parameters on both normal stress in the adherends and shear stress in the adhesive.

4.4 Adhesive Bond Thickness Results

Figures 1 and 2 show normalized stress in the GFRP face sheet and in the bias/silicon detector layers relative to the type of adhesive, adhesive bond thickness, and type of converter material specified in the legends of the graphs. The type of adhesive defines the limiting conditions of shear moduli being considered. On the upper end, rigid epoxy adhesives with shear moduli on the order of 95 ksi were used in the study, and on the lower end, compliant RTV silicone adhesives with shear moduli on the order of 75 psi were applied.

From figures 1 and 2, a couple of conclusions can be drawn. First, the shear modulus of the adhesive has a pronounced affect on the bond thickness necessary to isolate the converter layer from the GFRP face sheet or the bias sheet-silicon detector layer. The delta (Δ) between curves with everything the same except the adhesive type (epoxy versus RTV) is upwards of around three times the stress level. Second, the choice of converter material, lead versus tungsten, does have an affect on the stress levels in the adherends. Significant effort was put forth to determine why this change in adherend stress level did not exactly follow the ($\Delta\alpha$*E*RL) figure of merit initially used in ranking the converter materials. This issue is discussed in detail in section 5.0.

The baseline design for the SuperGLAST tracker trays was included in figures 1 and 2 to show the level of coupling between the conversion layer and both the GFRP face sheets and the bias circuit/silicon detector ladders. The silicon detectors are seeing maximum stress because of thermal expansion in the conversion layer. This coupling explains why such high stress levels were being predicted for the detectors.

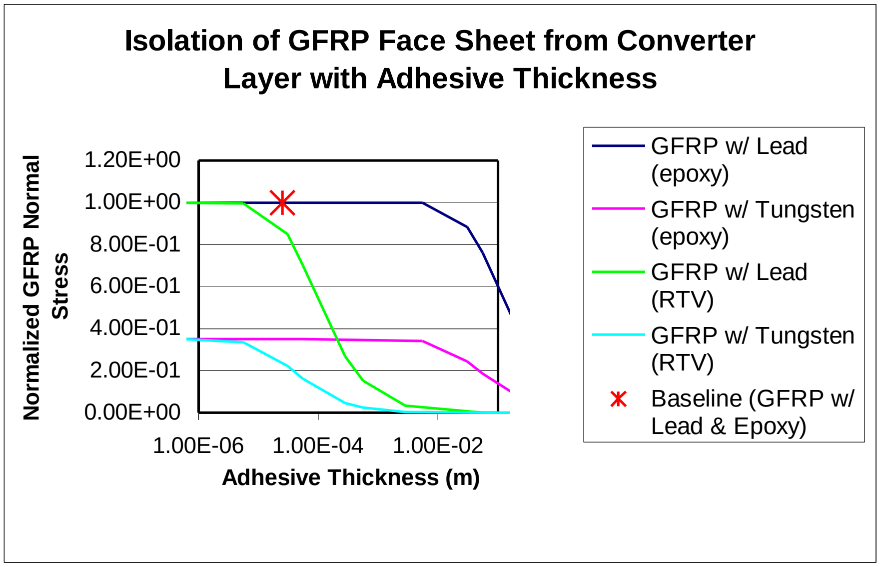

Figure 1. Isolation of GFRP Face Sheet from Converter Layer with Adhesive Thickness

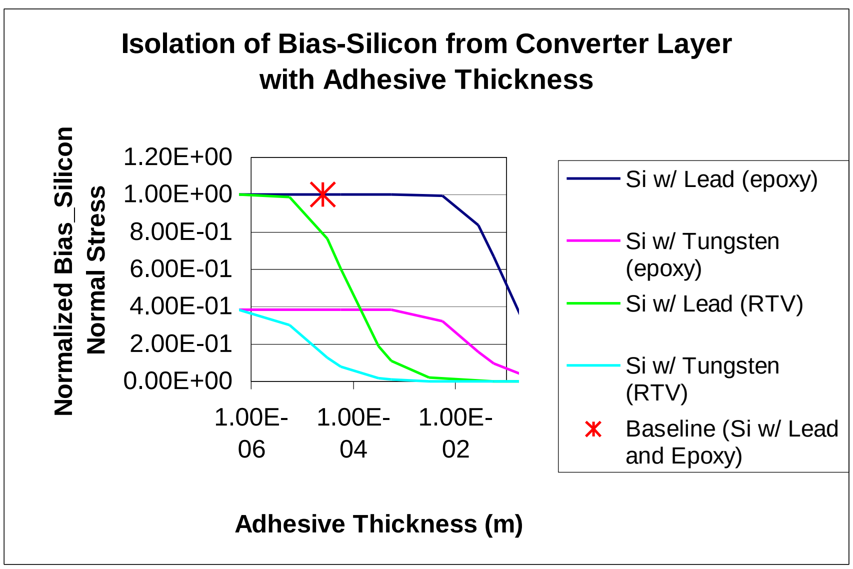

Figure 2. Isolation of Bias-Silicon from Converter Layer with Adhesive Thickness

In order to find the minimum adhesive bond thickness that isolates the conversion layer from the rest of the tracker tray, allowable design stress limits had to be set for the adhesive and the adherends first so that the calculated stresses in both do not exceed the yield strengths of the corresponding material. The allowable stress limits were set for the following materials based upon taking certain factors of safety on the yield strengths. Because a comparison needed to be made between epoxy and RTV, both allowable shear stress limits were formed from the shear strengths by the following method:

For Epoxy (based from WWW.MATweb.com) [3],

Shear Strength Range = 500psi to 3000psi

Safety Margin of 2 on Min. Shear Strength = 250psi

(Equivalent to Safety Factor of 7.0 on Average shear strength

for Epoxy material listed in HTN-102050-0017)

For RTV Silicone (based from WWW.MATweb.com) [3],

Shear Strength Range = 60psi to 300psi

Safety Margin of 2 on Min. Shear Strength = 30psi

(Equivalent to Safety Factor of 4.2 on Average shear strength

for RTV material listed in HTN-102050-0017)

Allowable stress limits for the converter materials were set the same way as the adhesives:

For Lead (Pb) (based from WWW.MATweb.com) [3],

Yield Strength = 2,610psi

Safety Margin of 2 on Yield Strength = 1,310psi

(Standard Margin of Safety for Actual Material Data)

For Tungsten (W) (based from WWW.MATweb.com) [3],

Yield Strength = 108,800psi

Safety Margin of 2 on Yield Strength = 54,400psi

(Standard Margin of Safety for Actual Material Data)

The allowable stress limits for silicon and GFRP are based upon the following:

For Detector Grade Silicon (based from HTN-102050-016) [4],

Ultimate Strength = 30,300psi

Standard Deviation = 6,000psi

Safety Margin of 7.4 on Strength = 4,100psi

(Ult.Str.-3*Std. Dev. plus an additional

Margin of Safety of 3.0 from NASA[5])

For GFRP (based on manufacturer's fiber/resin data),

Tensile Strength = ~330ksi

Safety Margin of 2 on Tensile Strength = 165ksi

(Standard Margin of Safety for Actual Material Data)

Using the allowable stress limits given above and the stress equations formulated in section 4.3, the adhesive thickness was optimized such that the stress in the adherend or shear stress in the bond did not exceed design limits. The minimum adhesive thickness was then recorded in table 2.

In looking at the results listed in table 2, using an adhesive with a shear modulus of RTV and a converter material similar to Tungsten would be the optimum choice. Lead could also be used as long as it is with an RTV type adhesive as well, but one should expect to have an adhesive bond thickness of 0.127 mm or greater in between the layers of the SuperGLAST tray payload. Stiffer adhesives with shear moduli greater than 100 psi are not a good choice because the bond thickness necessary to prevent failure is much greater than the baseline.

SuperGLAST CTE Mismatch Solution Type	Min Adhesive Layer Thickness between GFRP and Converter (mm)	Min Adhesive Layer Thickness between Si and Converter (mm)
Baseline	0.075	0.075
Epoxy w/ Lead @ allowable stress	73.66	91.44
RTV w/ Lead @ allowable stress	0.126	0.127
Epoxy w/ Tungsten @ allowable stress	0.1765	0.1181
RTV w/ Tungsten @ allowable stress	0.00929	0.00594

Table 2. Minimum Adhesive Thickness for Different Adherends and Adhesive Combinations.

Figure 3, graphs adhesive thickness versus total mass and separation distance for the cases with lead converters and either epoxy or RTV. As can be seen in the graph, the mass and the separation distance do not start to increase significantly until the adhesive thickness gets above about 0.1016mm (0.004"), thus advocating a maximum adhesive thickness from a adhesive mass and separation distance standpoint of 0.1016mm (0.004") for the design.

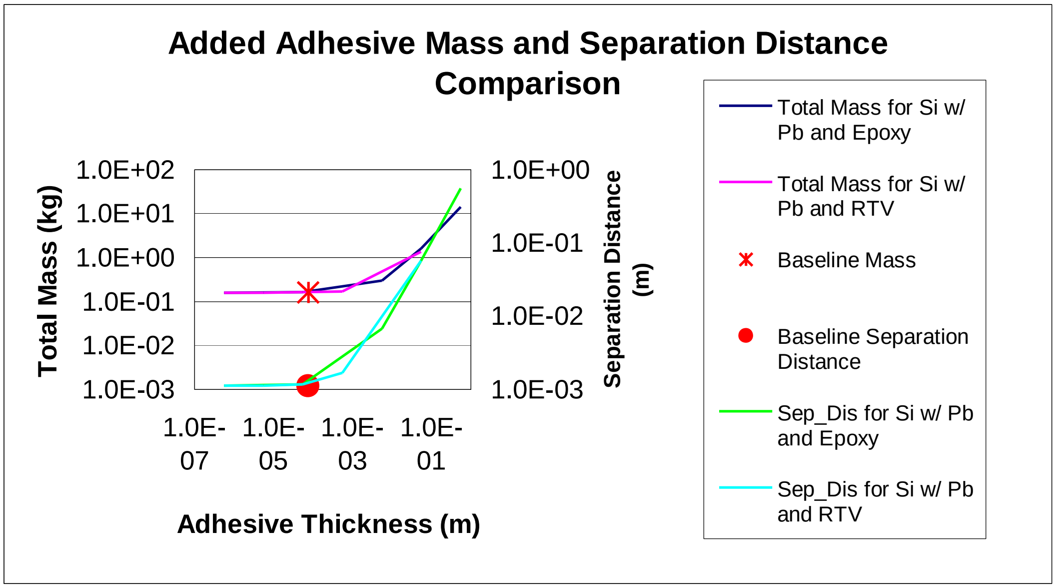

Figure 3. Added Adhesive Mass and Separation Distance Comparison

5. Converter Stress Response Analysis

The figure of merit used to rank the different converter materials was developed based on the stress relationship derived in section 4.3, equation (13). Equation (13) represents the stress level in an adherend that is bonded to the converter layer. Both thermal as well as structural properties (α, E, t) for the adherend appear in the expression. The thickness of the converter material is based upon the required 25% radiation length for SuperGLAST. The regular conversion trays for GLAST had a shorter radiation length requirement (2.5% RL).

5.1 **Material Properties for Conversion Layer:** r**, E, t, &** a

Converter Material	**Density,** r **(g/cm^3)**	**Elastic Modulus, E (GPa)**	**SuperGLAST Thickness, t 25% RL (mm)**	**Regular GLAST Thickness, t 2.5% RL (mm)**	**Coefficient of Thermal Expansion,** a **(ppm/^{o}C)**
Lead (Pb)	11.34	13.8	1.4	0.140	29.3
Tungsten (W)	19.30	386.1	0.875	0.0875	4.5
Gold (Au)	19.32	74.5	0.825	0.0825	14.2
Platinum (Pt)	21.45	146.9	0.75	0.075	9.0
Tantalum (Ta)	16.60	186.2	1.025	0.1025	6.5

Table 3. Material properties for GLAST Converter: r**, E, t, &** a

5.2 SuperGLAST Figure of Merit for Conversion Layer Material

The problem discovered with the figure of merit for SuperGLAST is the large dependence of the denominator ($E_1t_1 + E_2t_2$) in equation (13). The denominator is not significant for the regular GLAST trays because the original conversion material, lead, has a small E_2 and t_2, which reduced the significance of the ($E_1t_1 + E_2t_2$) expression in the equation. The figure of merit that was initially concluded for ranking converter material was $\Delta\alpha*E*t_{RL}$ for both SuperGLAST and regular GLAST tracker trays.

This however is not true for SuperGLAST where the thickness of the converter layer is an order of magnitude larger, and some of the other converter materials that were compared to lead have lower CTE values and higher elastic moduli. The combination of larger converter thickness and higher elastic modulus now makes the ($E_1t_1 + E_2t_2$) expression significant, and it should be included in the figure of merit for SuperGLAST. Using the figure of merit of $E_1*E_2*t_2*\Delta\alpha /(E_1t_1 + E_2t_2)$ for the ranking of converter materials, tungsten ranks as the best choice for SuperGLAST as can be seen in table 4.

Silicon Detector Properties		
Detector Elastic Modulus, E_1 (GPa)	**SuperGLAST Detector Thickness, t_1 (mm)**	**Detector CTE, a_1 (ppm/^{o}C)**
130.0	0.4	2.5

Converter Material	**Converter Elastic Modulus, E_2 (GPa)**	**SuperGLAST Converter Thickness, t_2 25% RL (mm)**	**Converter CTE, a_2 (ppm/^{o}C)**	**Normalized (to lead) Figure of Merit, $E_1E_2t_2Da/(E_1t_1+E_2t_2)$**
Lead (Pb)	13.8	1.4	29.3	1.0
Tungsten (W)	386.1	0.875	4.5	0.239
Gold (Au)	74.5	0.825	14.2	0.873
Platinum (Pt)	146.9	0.75	9.0	0.608
Tantalum (Ta)	186.2	1.025	6.5	0.433

Table 4. Figure of Merit for SuperGLAST Converter Materials

Figures 4 and 5 show the shift in the stress levels for the five converter materials based on radiation lengths of 2.5% and 25%. The adherend chosen to bond with the five different converter materials in the following graphs was detector grade silicon. The shift between the two graphs is evident for the five converter materials plotted. Lead has the greatest shift indicating a strong influence in the radiation length thickness of the converter material, and the CTE difference between lead and silicon. Tungsten does not cause an appreciable shift in the stress level of the silicon when the RL is increased to SuperGLAST.

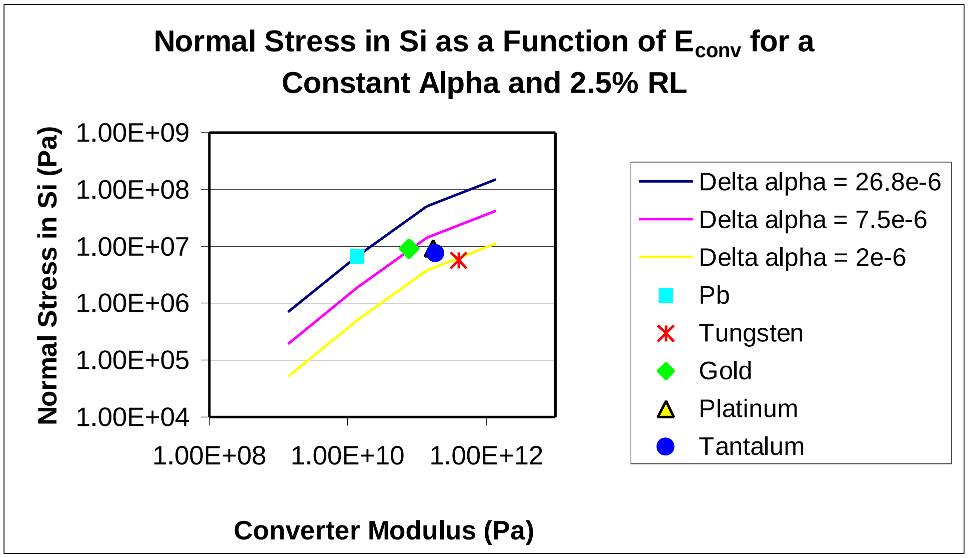

Figure 4. Normal Stress in an Adherend bonded to Different Converter Materials (2.5% RL)

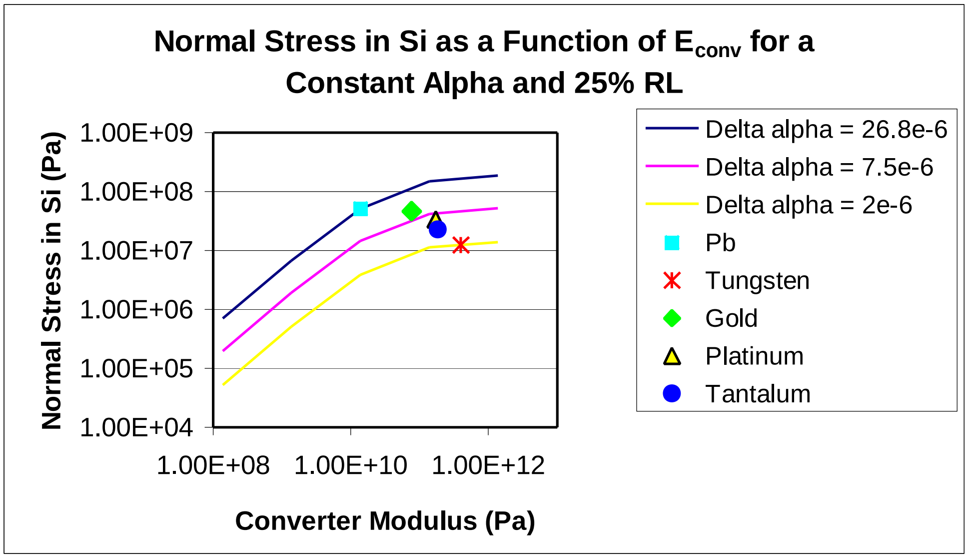

Figure 5. Normal Stress in an Adherend bonded to Different Converter Materials (25% RL)

6. Conclusions

The SuperGLAST payload design has a couple of unique design issues surrounding the adhesive used to bond the layers of the payload. The shear modulus is inversely proportional to adhesive thickness, which shows that adhesives with a lower shear modulus have a smaller bond thickness for the allowable design stress limits. From analytical models, an adhesive shear modulus less than 100 psi is preferable. Bond thickness in turn controls GLAST tracker tray mass and detector/converter separation distance. Minimizing the bond thickness below 0.004" proved to be better for tray mass and detector/converter separation distance. The selection of converter material further reduced stresses in all the layers of the payload. Based on the new figure of merit for the SuperGLAST trays, tungsten appears to be more attractive as the converter material.

One issue that still needs to be address with future testing is the issue of adhesive bond strength and adherend surface preparation. Ultimately, the maximum bond strength of an adhesive will determine whether an adhesive can survive the extreme thermal conditions that the GLAST tracker trays are going to be exposed to in space. Unfortunately, that is not something that can be determined from the analysis done here. Only testing of selected adhesives will provide the solution to this issue.

7. References

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