CTE Mismatch Summary Report of the Current Baseline Design

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Abstract

Recent testing and analysis have identified a CTE mismatch issue between the silicon ladders and the converter layer for the SuperGLAST payload design. This note summarizes the current tracker tray payload attachment baseline design concepts for the *standard* tray (2.5% RL) and SuperGLAST tray (25% RL). Supporting analysis is presented for each concept in addition to summarizing design options to mitigate these CTE mismatch issues. Information presented here is intended to open channels of communication and identify viable solutions.

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1. Definitions

CTE:	Coefficient of (linear) Thermal Expansion.
CyE:	Cyanate Ester.
GFRP:	Graphite Fiber Reinforced Plastic.
E:	Modulus of Elasticity.
FEA:	Finite Element Analysis.
FEM:	Finite Element Model.
MMC:	Metal Matrix Composite.
Pb:	Lead
ppm:	parts per million.
RL:	Radiation Length in cm.

2. Introduction

Recent thermal testing of the prototype tray and ladder test fixture have revealed a possible problem due to the CTE mismatch between the silicon and lead converter layers. As a result, special attention is required to address and correct this issue. At the present, several design options have been identified and are being investigated. Some of these options will be analyzed and the results of these analyses will be presented in a future technical note.

This technical note summarizes the baseline tray payload design for both the *standard* tray (2.5% RL) and the SuperGLAST tray (25% RL). Baseline design choices and calculated stress levels are presented. In addition, a summary of the baseline analysis defines possible CTE mismatch issues and presents options available to correct these issues.

3. Summary of Baseline Design

The baseline tracker tray design is summarized herein for both the standard and SuperGLAST converter layers. Each tray is constructed as a honeycomb sandwich structure with the payload bonded to both sides. Face sheet options, converter layer materials and thickness' are presented along with payload requirements.

3.1 *Standard* Tray Baseline

The *standard* tracker tray design uses an aluminum closeout frame and aluminum honeycomb core, bonded between two face sheets to make up the structural components of the tray. Several face sheet materials have been considered and/or used in prototypes, these include: a 50 μm aluminum face sheet, a 75 μm 0/90 plain balanced weave fabric GFRP face sheet and a 318 μm 6-ply quasi-isotropic GFRP face sheet. The GFRP face sheets are made of a P75 fiber and RS-11 epoxy matrix. GFRP face sheets have a definite advantage over aluminum because of their long RL, higher modulus and slightly negative CTE. For comparison and completeness, both are discussed herein.

The payload is bonded to the tray face sheets on both sides. The payload is defined here as the non-structural elements that will be post-bonded to the structural tray. This includes the converter layer, bias-circuit layer(s) and detector layer(s). Note that the converter layer is only bonded to the bottom side of the tray, which allows the conversion to occur closer to the silicon detector pairs (X and Y). Figure 1 shows the bottom payload. In the baseline design, lead is being used as the converter material because of its high RL and low modulus. For converters rigidly bonded to the rest of the tray and payload, the figure of merit used to select lead as the baseline converter is the product of the RL, CTE and E. Several short RL materials options are available, however lead proves to be ideal. This is discussed in section 5.1.1. The bias-circuit is a kapton/copper laminate co-cured with an epoxy matrix. Silicon strip detectors (cut in the 111 plane) are edge bonded together to form a detector ladder, complete the tray payload.

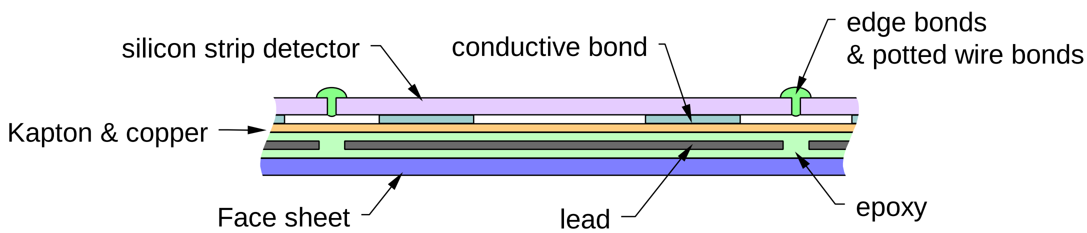

Figure 1: Cross-section schematic of bottom payload simulation (a top payload has no lead converters).

The *standard* tray design includes a 2.5% RL baseline converter layer. This is equivalent to a minimum lead thickness of 140 µm. The bias-circuit has a thickness of 118 µm and the silicon detectors have a thickness of 400 µm. The epoxy bond layers vary in thickness between 75 µm and 125 µm.

***** NOTE: A key statement in this section is that the payload layers are all bonded with RIGID thermoset adhesives.***

3.2 SuperGLAST Baseline

The engineering effort for the SuperGLAST tray has not been as extensive as that of the *standard* tray design. For this reason, the SuperGLAST baseline tray design concept is nearly identical to the *standard* tray baseline with the exception of the converter layer thickness. The closeout frame and honeycomb core remain the same although optimization of the structural components is necessary to increase tray stiffness. The face sheet options include the P75/RS-11 GFRP, but do not include aluminum as a viable option. The aluminum face sheets produce high stresses in the silicon because of their high CTE in combination with the thickness of the lead converter.

With the exception of the converter thickness, the baseline SuperGLAST payload design is identical to the *standard* tray. The converter layer has been increased from 2.5% to 25% for these trays. This is equivalent to a lead thickness of 1400 μm.

***** NOTE: A key statement in this section is that the payload layers are all bonded with RIGID thermoset adhesives.***

4. Summary of Stress Analysis of Baseline Designs

4.1 Stress Analysis of the Payload

A stress analysis of the payload was performed to investigate the net effect on stress levels in the silicon that resulted from the CTE mismatch between the silicon and other payload layers. To briefly explain, the payload elements (silicon, bias-circuit and converter layer) are bonded together and to the face sheets using rigid room temperature curing adhesives. The baseline design used a minimum bond thickness to minimize weight. As a result, the payload layers are mechanically coupled and the total strain of each layer is equal when subjected to a temperature change (neglecting bending effects). The total strain is defined as the thermal strain added to the mechanical strain. The thermal strain is the product of the temperature change by the CTE of the material. The mechanical strain is a result of the CTE mismatch between adjacent layers. The thermal expansion of one layer causes traction stresses in adjacent layers and compression stresses within itself (or vice-versa).

A simple, closed-form analysis was performed to predict the mechanical stress in the silicon layer for the top and bottom payloads that result from the CTE mismatch. Several key assumptions were made to simplify the analysis; these are:

- The CTE, modulus of elasticity and shear modulus of the aluminum honeycomb core were assumed zero. This assumption mechanically isolates the top payload from the bottom payload.
- All adhesive bond joints were neglected. This assumption neglects the CTE effects and any shear compliance of the adhesive. It was found using FEA models that this assumption only had a ~5% effect on the overall stress levels in the silicon.
- Membrane stresses in the face sheets that result from the addition of the closeout frame have been neglected. This effect is conservative and will need to be investigated.

These assumptions, although mostly conservative, were validated using a FEM. FEA thermal stress results corroborated the results of the closed-form analysis.

4.2 Discussion of Results

The results of the stress analysis for the baseline designs are given in Table 2. Mechanical stress levels in the silicon are given for the top and bottom of the tray. The equilibrium (zero) stress state was assumed to be at 21°C and all the values listed in Table 2 are maximum values at -30°C.

Table 2: Summary of mechanical stress values in the silicon (these values are maximums at -30°C).

Facesheet Material	Maximum Normal Stress in Silicon	
	Bottom (psi)	Top (psi)
2.5% RL Converter (Standard)		
318 μm P75/RS-11 (GFRP)	40	651
75 μm P75/RS-11 (GFRP)	-446	272
50 μm Aluminum	-2436	-1640
25% RL Converter (SuperGLAST)		
318 μm P75/RS-11 (GFRP)	-4412	651
75 μm P75/RS-11 (GFRP)	-5491	272
Decoupling Bias-Circuit from Face Sheet/Converter Layer		
Si Ladder & Bias-Circuit	-414	-414
** A negative value indicates compression **		

The stress levels in the 2.5% RL converter trays are reasonably low overall. The GFRP stress levels are very low and the aluminum facesheet levels are just below –2500 psi. Stress levels of the SuperGLAST trays nearly reach –5500 psi. This certainly warrants further investigation.

For comparison, the silicon and bias-circuit layers were considered mechanically decoupled from the converter layer and facesheet. The net result is a reduction in the stress level of the silicon relative to the SuperGLAST trays. The *standard* tray, however, does not show this advantage. In the case of the 318 μm GFRP facesheet (2.5% converter), the lead converter layer actually reduces the stress level on the bottom of the tray. In the case of the 75 μm GFRP facesheet (2.5% converter), the thinner facesheet reduces the stress level on the top of the tray. It is worth noting that the stress levels presented in this report are preliminary estimates of the expected stresses.

4.3 Result Conclusions

The question still remains: "what impact do these stress levels have on the survivability of the silicon to the thermal environment expected?" To fully answer this question, the ultimate stress of silicon must be known. Investigation into the strength of silicon has shown that a variety of values can be obtained. Published data can be found that claims an ultimate strength of 10 to 50 ksi, 10 to 99 ksi and even 218 to 1305 ksi. If micro cracks are considered, the strength values drop by as much as an order of magnitude. Personal experience of HYTEC engineers claim strength properties between 3 to 5 ksi should be expected. With such a variety of information, it seems absolutely necessary to test 'ACTUAL' strip detectors to determine the mechanical properties (modulus & ultimate strength) of the silicon detectors used for the GLAST program.

Recently, HYTEC engineers performed a simple 3-point bend test on several silicon samples. Samples were salvaged from the prototype tray and ladder test piece used in the thermal tests. The 3-point bend test is a quick method of measuring the ultimate strength of the silicon. Eleven samples in all were tested and a mean ultimate strength of 30,300 psi was measured with a standard deviation of 6,000 psi. Assuming a normal distribution, the ultimate strength would be 12,380 psi (mean less 3σ). Including a factor of safety of 3.0 (taken from NASA-STD-5001, Structural Design and Test Factors of Safety for Spacecraft Hardware), the design stress levels should not exceed 4,125 psi.

With the design stress level defined to be 4,125 psi, it is clear that the CTE mismatch of the silicon, lead and carbon face sheets does not induce significant stress levels to warrant modifications to the baseline design for the *standard* tray. A factor of safety of 6.3 on the design level is computed.

The SuperGLAST tray, however, exceeds this design level, although not by much. Until additional testing shows that the ultimate strength of silicon can be predicted with a higher degree of accuracy and the dispersion is such that the design limit loads can be raised, the SuperGLAST CTE mismatch issue must be addressed. The following sections identify design options to address these SuperGLAST issues.

5. Summary of CTE Mismatch Design Options

Recently, HYTEC engineers gathered to identify the possible solutions to correct the CTE mismatch issue on the SuperGLAST trays. The goal was to identify all solutions that would reduce the thermally induced stress in the silicon. Adhesive selection was neglected during these talks and will require some design and analysis to ensure interlaminar shear stresses are minimized.

Possible design options were identified and categorized. Three categories were used to describe each design approach. These are the low effective CTE options, mechanical decoupling design options and environmental design options. Each is described in the following paragraphs.

5.1 Low Effective CTE Converter Design Options

This first approach considers methods of reducing the overall or effective CTE of the bias-circuit, converter layer and structural face sheet to more closely match the CTE of silicon. The result is a substantial reduction of the normal stress in the silicon. There are several options available and are briefly discussed in the following paragraphs.

5.1.1 Alternate Materials

Several short RL materials options are available and can be substituted for lead as the converter material with improved (more closely matched to silicon) CTE properties. These include tungsten, tantalum, platinum and gold to name a few. However, the level of stress induced in the silicon is a function of the CTE differential with silicon, modulus of elasticity and thickness of the converter, for a rigidly bonded converter. For this reason, all three values must be considered to determine the optimal converter material. Using,

$$(CTE_{converter} - CTE_{silicon}) \text{ x } E \text{ x } RL$$

as the figure of merit, lead proves to be the most ideal converter material. This is shown in Table 1.

Table 1: Converter material options as compared to lead; the figure of merit is a measure of the converter's tendency to induce thermal stresses when rigidly bonded to the rest of the tray/payload assembly.

	ΔCTE×E×RL (normalized to lead)
Lead	1
gold	1.37
platinum	1.35
tantalum	1.37
tungsten	1.12

Unlike rigidly bonded converters, thicker, more compliant adhesive layers reduce the maximum stress levels in the silicon. In such cases, the modulus of elasticity becomes less dominant, and the differential shear deformation between the converter and adjacent layers becomes more significant. Therefore, minimizing the differential CTE between the converter and silicon/face sheet will minimize both the nominal stress in the silicon as well as the separation distance between the converter and silicon. For this reason, the figure of merit used for compliant adhesive layers includes only the CTE and RL (modulus of elasticity is neglected). Again, these alternate material options are compared to lead and the results are summarized in Table 2. Using,

$$(CTE_{converter} - CTE_{silicon}) \times RL$$

as the figure of merit, tungsten proves to be an ideal material when thicker, more compliant adhesive layers are used.

Table 2: Converter material options as compared to lead; the figure of merit is a measure of the converter's tendency to separate the converter and detectors when isolated from the rest of the tray/payload assembly.

	ΔCTE×RL (normalized to lead)
Lead	1
gold	0.25
platinum	0.13
tantalum	0.10
tungsten	0.04

5.1.2 Lead Matrix Composites

Recently, a technical note (HTN-102050-0011) was presented to examine several options for building lead sheets with a minimum CTE mismatch to that of silicon. Two general categories were discussed. Here, the option of using lead as a matrix material to form a metal matrix composite with a low effective CTE is considered.

Lead can be used as a matrix material to form a carbon reinforced metal matrix composite. Both carbon fibers and Reticulated Vitreous Carbon (RVC) foam were discussed as possible candidates as the reinforcing material. Such techniques have been successfully fabricated using aluminum, copper, titanium and other metals, but not with lead. These options would require a fair amount of research, design and testing to ensure their feasibility and incorporate into the SuperGLAST tray design.

5.1.3 Lamination of Lead as a Sandwich Structure

In addition to lead matrix composites, HTN-102050-0011 discussed the use of lead laminated with carbon composites and lead laminated with Invar. These options include co-curing Pb with GFRP, bonding Pb with GFRP, and bonding Pb with Invar.

Co-curing is a reasonable option, although there is a moderate penalty from the added thickness of the GFRP layers. Co-curing Pb and GFRP will require proof testing to ensure an adequate bond can be achieved that can survive the temperature extremes expected.

Bonding is a proven option, although there is a substantial penalty from the added thickness and mass associated with the addition of the bond layer between each lamina. High modulus fibers can be used to reduce these penalties, however cost then becomes a factor.

5.1.4 Powdered Lead Composites

Powdered lead matrix was discussed as an alternate option. Here, powdered Pb would be mixed with a low-CTE adhesive and used to bond the bias-circuit to the facesheet, to the proper thickness. This would require a fair amount of R&D to ensure adequate consistency of the Pb/epoxy as the converter layer, as well as validating the feasibility. Currently, this option is receiving minimal attention from engineers because it is unlikely that that a low CTE matrix material is available.

5.1.5 Discontinuous Lead (Slits)

A final decoupling option was considered for completeness. Here, the lead converter layer is no longer a continuous sheet, but is filled with small slots. The expansion forces are minimized and can be easily constrained by the face sheet. A number of questions arise, such as the effectiveness of a discontinuous sheet in addition to the net results if an adhesive fills these gaps and cancels the flexural effect. This option is not being considered at this time.

5.2 Options to Decouple the Converter Layer from the Silicon

Here, options are described to decouple the converter layer from the silicon. Decoupling options range from those that include a compliant layer between the silicon or silicon/bias-circuit and the converter layer to options that mechanically isolate the converter layer. Unlike the low CTE options, using an alternate material to replace the lead converter layer is desirable because closely matching the CTE will reduce shear strains and ultimately bond layer thickness'. Several options are identified and briefly described below to decouple the converter layer from the silicon.

5.2.1 Embed/Move Converter Layer within Core

One option considered is to move the converter layer and embed the converter material within the core. Mechanically, this becomes very difficult. The converter layer may be arranged such that the converter material (in this case lead) fills the hexagonal spaces of the honeycomb core, which results in a discontinuous converter layer. A second option is to trap the converter layer between the core and face sheet. The integrity of the face sheet to core bond strength will need to be investigated to ensure enough surface area/bond strength. There are a number of questions as to how this is done and what is the quality of the final structure. Due to complexity, this option is not being considered at this time.

5.2.2 Capture Converter Layer between Face sheets

This option can be described as a subset of the bonded laminate option. Here, the converter layer is mechanically isolated from the silicon by entrapping it between two face sheets. An egg-crate-like structure may be used to house the converters, and the upper face sheet shall support the bias-circuit and silicon payload. Lead as a converter material becomes less desirable due to the large CTE. A lower CTE will reduce the space required to allow expansion of the converter material.

A definite concern is the movement of the converters when subjected to launch vibrations. To accommodate such motions, the converter layer will need to be fixed. A compliant layer may be used in this case to allow free expansion to thermal loads, but constrain the layer under dynamic load conditions.

One downside to this approach is the separation distance between the converter layer and the silicon increases. This shall be addressed in later analysis.

5.2.3 Compliant Boundary Layers

Compliant boundary layers are also a viable option. Compliant boundary layers allow free expansion of the converter layer to adjacent adherends without transferring significant shear strain that result from the CTE mismatch. This allows the silicon to be mechanically isolated without large separation of the converter layer to the silicon and face sheets. There are several options for materials and locations for the compliant layer. The types of options are discussed below.

5.2.3.1 <u>Elastic compliant layers Versus Plastic compliant layers</u>

Two types of compliant layers can be used, Elastic vs. Plastic. Elastic boundary layers are those that allow free expansion without altering the physical characteristics of the compliant layer. Various adhesives and RTV's can be used here. Plastic boundary layers allow the free expansion of two adherends by allowing one to slide past the other. Grease is a perfect example of a plastic compliant layer.

Plastic boundary layers have an advantage by allowing for greater free expansion without a substantial weight penalty, and minimize the separation distance between the converter and silicon layers. However, plastic boundary layers have a definite disadvantage over elastic boundary layers. The converter and bias-circuit/silicon are held together by adhesion forces from the grease. Given that these forces are fairly low and that grease will flow, it is easy to see that it will be very difficult, if not impossible, to constrain the detectors and maintain the tight alignment requirements.

Elastic boundary layers also have some issues to address. Thick layers may allow too much motion during random vibrations, resulting in collisions between adjacent ladders of a single tray. Although this seems unlikely, it must be examined.

5.2.3.2 Compliant Layer Location Options

Two locations for the compliant layer can be considered. The compliant layer can be used to isolate the converter material, in which case other material options should be considered, or the compliant layer can be used to isolate the silicon, in which case shear stress issues between the SuperGLAST converter and face sheets must be examined. Both options will be investigated.

5.3 Environmental Design Option

This option is presented here only for completeness and is not being considered at this time. The proposed alternative to physically altering the tracker payload attachment structure is to reduce the thermal load on the tracker. This would required that the thermal design of the instrument radiators and heaters was such that the tracker could be assured to see minimal changes in temperature, say 0°C to 30°C. With this comes an unacceptably high risk as well as cost to design and provide hardware to ensure this type of temperature environment. Without a low cost, low risk solution, this option is not acceptable.

6. Conclusions

Each design option presented above has a number of issues that must be addressed before the optimum solution can be defined. Design issues such as mass, cost and separation between converter and silicon are only a few of the issues that must be examined. Some preliminary engineering addressed several of the low effective CTE options, therefore, attention is being focused on investigating the decoupling options. Two options that seem to stand out are the mechanical isolation of the converter (section 5.2.2) and the compliant layer (section 5.2.3). These options are being investigated and the results shall be presented in a follow-up technical report.