HTN-102050-0011
04/18/00

Building Lead Sheets with Minimum CTE Mismatch with Silicon: Conceptual Design Notes

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April 18, 2000

Abstract

This note summarizes conceptual design calculations for various approaches to build "low-effective-CTE" lead sheets. The options examined are sandwiches of pure lead and graphite fiber composites, either co-cured or secondary bonded, bonded Invar-lead sandwiches, and lead matrix graphite fiber composites. Sizing calculations are summarized and the various options are compared in terms of final effective CTE, total thickness, RL, and mass, and manufacturing considerations.

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1. Definitions

CyE: Cyanate Ester.
GFRP: Graphite Fiber Reinforced Plastic.
CTE: Coefficient of (linear) Thermal Expansion.
FE(M): Finite Element (Model).
RL: Radiation Length in cm
ppm: part per million
MMC: Metal Matrix Composite

2. Motivation

The GLAST tracker system uses large area silicon strip detectors and lead conversion layers. In those designs, the silicon and lead layers are essentially bonded together and constitute two layers of a multi-layer laminate. These systems are assembled at room temperature (21ºC) with room-temperature-curing adhesives. They will be flown into space and must survive relatively large temperature variations (approximately +50ºC to -30ºC). Studies have shown that dangerous levels of thermal stresses can be induced in the Silicon detectors, in part because of the large CTE mismatch between lead and silicon. This is especially true for the so-called SuperGLAST designs, which use a 1.4mm (25% RL) thick lead converter.

One option to alleviate the thermal stress issue may be to reduce the effective CTE of the converter sheets by using composites of lead and other (lower CTE) materials instead of pure lead sheets. The effective CTE of the composite could then be designed to match that of silicon as closely as possible.

Since lead has a very high positive CTE (29.3×10^{-6}/ºC), it must be balanced with materials with CTE's lower than that of Silicon (about 2.6×10^{-6}/ºC at room temperature but temperature dependent). To minimize added thickness and mass, the candidate materials should have Young's moduli as high as possible and CTE's as low as possible, certainly lower than 2.6×10^{-6}/ºC, or even negative. High modulus graphite fibers are ideal in that respect, since they exhibit extremely high modulus and slightly negative CTE. Sandwiches of lead and graphite fiber based composites are considered. A more development-intensive option of making a graphite fiber/lead metal matrix composites is also included, as well as a composite of Invar and lead sheets, as suggested by our Italian collaborators.

3. Assumptions

For this initial study, we considered designing lead converters with a total thickness of 25% of a radiation length, to a target effective CTE of 2.6×10^{-6}/ºC, roughly equal to the CTE of silicon at room temperature.

The lead in the designs was assumed essentially pure[1], with a Young's modulus of 13.79 GPa, specific mass of 11340 kg/m^3, and CTE of 29.34×10^{-6}/ºC.

For secondary bonded options, a generic epoxy adhesive was assumed with E=3.0 GPa, a specific mass of 1200 kg/m^3, a CTE of 60×10^{-6}/ºC, and bond thickness of 50 μm.

Any residual stress calculation assumes assembly at 21ºC, and survival temperatures between -30ºC and +50ºC.

4. Effective In-Plane CTE of Layered Sandwiches

The effective CTE of a sandwich of different isotropic materials (with identical Poison's ratios) is easily calculated by writing mechanical equilibrium of the sandwich. After solving for the effective CTE, one finds:

$$\alpha_{eff} = \frac{\sum_{i=1}^{n} \alpha_i E_i t_i}{\sum_{i=1}^{n} E_i t_i}, \qquad (1)$$

where α_{eff} is the effective CTE of a sandwich of n layers, and α_i, E_i, and t_i are the CTE, Young's modulus, and thickness of layer i.

In the cases where some layers are fiber reinforced composite materials, this relation holds only for quasi-isotropic layers ($[0/60/-60]_n$ and $[0/45/-45/90]_n$) for example. For other laminates, in-plane elastic properties are direction-dependent and complete 2x2 elasticity relations must be used. However, Eq. (1) is still useful to get a first order approximation and understand trends.

5. Low CTE Lead Sheet Design Options

5.1 Co-cured Graphite Fiber/Resin composite and Lead Sandwich

Sandwiches of lead and resin based graphite fiber composites could be built by co-curing GFRP prepregs with lead sheets. The obvious issues with this approach would be the thermal stresses in the lead layers and the interlaminar shear stresses induced by cooling the plates from cure temperatures (around 120ºC to 170ºC for typical resin systems) to room temperature and below. To minimize the shear stresses, large numbers of very thin layers of lead and GFRP could be used. Resin systems that can be cured at relatively low temperatures would also be preferable. Any chemical interaction between the fibers, resin system, and lead would also have to be considered.

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[1] containing at least 99.4% lead by weight, UNS numbers 50001 to 50042.

Fiber orientations in the GFRP layers must at least be balanced and isotropic for direct stresses; the simplest option is to use either a balanced 0/90 plain weave fabric (or a 2-layer [0/90] laminate of unidirectional fibers).

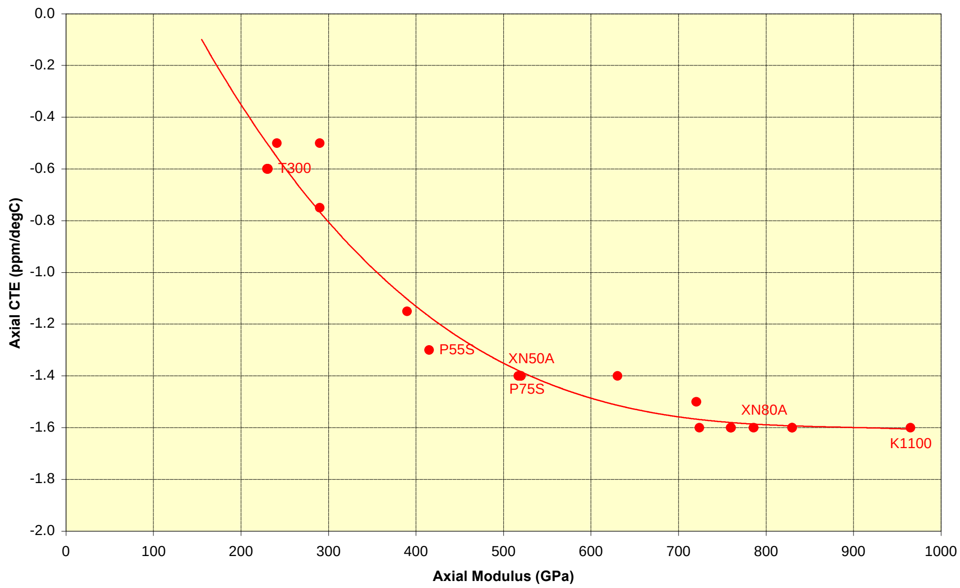

Figure 1: Modulus-CTE correlation in high modulus graphite fibers.

Fiber selection is a tradeoff between cost and mass and thickness penalty. As illustrated in Fig. 1, higher modulus fibers also have more negative CTE; as shown by eq. (1), both the higher modulus and the more negative CTE contribute to reduce the required total thickness of GFRP layers to achieve a specific goal for the effective CTE of the sandwich (i.e. that of silicon, or about $2.6\times10^{-6}/^{o}C$).

For illustration, we designed two examples of such laminates using two different fiber systems:

- XN50A, a common mid-range high modulus (517 GPa) fiber from Nippon. The elastic properties of XN50A are similar to those of other widespread fibers such as P75S from Amoco, M50J from Toray, or the new YSH-50A from Nippon.
- P120S, a high-end ultra-high modulus (848 GPa) fiber made by Amoco. P120S is somewhat similar to K13C2U from Mitsubishi, and YS-90A and XN85A from Nippon.

Both designs are based on the assumption that 0/90 balanced fabric prepreg is available for both fiber types, in 75 micron thickness per ply (after cure), and that a final fiber volume content of 50% (25% in each direction) can be achieved. Micro-mechanical analysis was used to estimate the properties of the GFRP layers from fiber and matrix properties (using the composites design code *ESAComp* from University of Helsinki, Finland). For the purpose of this initial study, the matrix was assumed to be a generic space qualified epoxy system (like the widely used 934 from Hexcel for example). The results are shown in Fig. 2.

Ply : **Carbon;XN-50A/Epoxy;Generic/V_f=50,f_1=50 (1)**

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Physical nature : **reinf.ply** Mech. behavior : **orthotropic**
Form of reinf. : -

t = - mm	m_A = - g/m²	V_f = 50%
	rho = 1720 kg/m³	f_1/2 = 50/50%

Engineering constants (orthotropic)

E_1 = 133.308GPa	G_12 = 2.81266GPa	nu_12 = 0.0126108
E_2 = 133.308GPa	G_31 = - GPa	nu_13 = -
E_3 = 133.308GPa	G_23 = - GPa	nu_23 = -

Thermal and moisture expansion coeff (orthotropic)

alpha_1 = 0.581884e-6/°C	beta_1 = 0 e-2/w%
alpha_2 = 0.581884e-6/°C	beta_2 = 0 e-2/w%
alpha_3 = 0.581884e-6/°C	beta_3 = 0 e-2/w%

Ply : **P-120S;10/2180/Epoxy;Generic/V_f=50,f_1=50 (1)**

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Physical nature : **reinf.ply** Mech. behavior : **orthotropic**
Form of reinf. : weave, plain

t = 0.075mm	m_A = 130.5g/m²	V_f = 50%
	rho = 1740 kg/m³	f_1/2 = 50/50%

Engineering constants (orthotropic)

E_1 = 210.57GPa	G_12 = 2.93059GPa	nu_12 = 0.00733594
E_2 = 210.57GPa	G_31 = - GPa	nu_13 = -
E_3 = 210.57GPa	G_23 = - GPa	nu_23 = -

Thermal and moisture expansion coeff (orthotropic)

alpha_1 = -0.314685e-6/°C	beta_1 = 0 e-2/w%
alpha_2 = -0.314685e-6/°C	beta_2 = 0 e-2/w%
alpha_3 = -0.314685e-6/°C	beta_3 = 0 e-2/w%

Figure 2: Elastic properties of XN50A/Epoxy and P120S/Epoxy balanced plain fabric layers as estimated from micro-mechanical analysis.

Using these properties for the graphite/epoxy layers, Eq. (1), and a total lead thickness of 1.40mm (25% RL), we calculate a first approximation of the total thickness of graphite/epoxy required to achieve an effective CTE of the laminate of 2.6×10^{-6}/°C. Those thicknesses are then fine-tuned using micro-mechanical analysis to achieve the desired result, as shown in Fig. 3.

Laminate engineering constants and expansion coeff

Laminate : **[XN50/Ep 0/90 75micron] *37 + [Pb 38.9micron]*36**
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Lay-up : (0a/(0b[t=0.0389]/0a)36) [mm]

Ply
a Carbon;XN-50A/Epoxy;Generic/V_f=50,f_1=50 (1) 75micron
b Metal;lead

Moduli (GPa)

In-plane		Flexural	
E_x	= 93.62	E^f_x	= 95.06
E_y	= 93.62	E^f_y	= 95.06
G_xy	= 3.65	G^f_xy	= 3.62

Poisson's ratios

nu_xy	= 0.0282	nu_yx	= 0.0282

Thermal expansion coefficients

In-plane	e-6/°C	Curvat.	(1/m)/°C
alpha_x	= 2.55	delta_x	= 0
alpha_y	= 2.55	delta_y	= 0
alpha_xy	= 0	delta_xy	= 0

Laminate engineering constants and expansion coeff

Laminate : **[P120/Ep 0/90 75 micron]*15 + [Pb 100micron]*14**
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Lay-up : (0a/(0b[t=0.1]/0a)14) [mm]

Ply
a P-120S;10/2180/Epoxy;Generic/V_f=50,f_1=50 (1) 75 micron
b Metal;lead

Moduli (GPa)

In-plane		Flexural	
E_x	= 102.12	E^f_x	= 108.83
E_y	= 102.12	E^f_y	= 108.83
G_xy	= 4.25	G^f_xy	= 4.17

Poisson's ratios

nu_xy	= 0.0314	nu_yx	= 0.0314

Thermal expansion coefficients

In-plane	e-6/°C	Curvat.	(1/m)/°C
alpha_x	= 2.76	delta_x	= 0
alpha_y	= 2.76	delta_y	= 0
alpha_xy	= 0	delta_xy	= 0

Figure 3: Elastic properties of symmetric laminates of lead and GFRP based on XN50A/Epoxy (left) and P120S/Epoxy (right) balanced plain fabric layers; both examples achieve an effective CTE very close to that of silicon (2.6×10^{-6}/°C).

Table 1 summarizes the two designs. Note that the 75-micron fabric layer assumed in the designs is a lower bound of commercially available fabrics. Both designs would be revised after selecting a fiber/matrix system and a supplier for the fabric prepreg.

GFRP Layers						Lead Layers			Total
type	E (GPa)	α (10^{-6}/ºC)	t (µm)	n	T=n×t (µm)	t (µm)	n	T=n×t (µm)	T (µm)
XN50A/Ep	133.3	0.582	75	37	2775	38.9	36	1400	4175
P120S/Ep	210.6	-0.315	75	15	1125	100.0	14	1400	2525

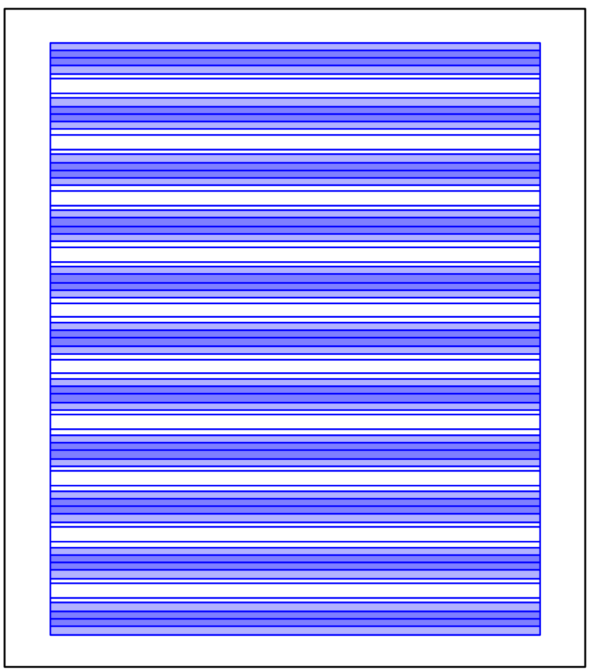
Table 1: Two Examples of Co-cured lead/GFRP laminates with effective CTE of 2.6ppm/degC.

5.2 Secondary Bonded Graphite Fiber/Resin Composite and Lead Sandwich

An alternative to the co-cured laminate approach of the previous section would consist of bonding together, with room–temperature-curing adhesives, layers of lead and pre-cured thin plates of GFRP.

The advantage is a substantial reduction in the total temperature change experienced by the laminate (no high temperature cure involved). Because of the smaller temperature difference, the thickness of individual layers of lead can be larger; however, thicker layers also lead to increased interlaminar shear stresses near the edges.

The negatives include a build up of additional adhesive layers between the GFRP and the lead (typically 50 to 75 micron thick each), and an additional step of fabrication.



Laminate engineering constants and expansion coefficient

Laminate : postbonded XN50/Ep and lead sandwich
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Lay-up : (0a/+45a/+45a/0a/(0b/0c[t=0.14]/0b/0a/+45a/+45a/0a)10) [n

Ply
a Carbon;XN-50A/Epoxy;Generic/V_f=50,f_1=50 (1) 75micron
b generic epoxy bond layer (50 micron)
c Metal;lead

Moduli (GPa)

In-plane			Flexural		
E_x	=	56.60	E^f_x	=	60.44
E_y	=	56.60	E^f_y	=	60.44
G_xy	=	21.37	G^f_xy	=	22.75

Poisson's ratios

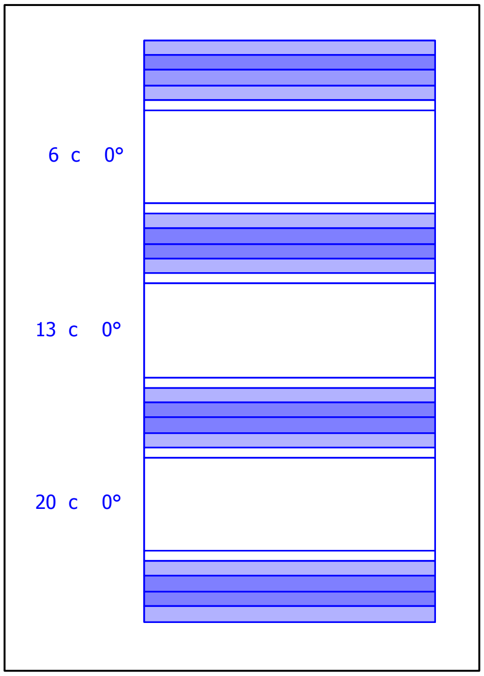
nu_xy	=	0.324	nu_yx	=	0.324

Thermal expansion coefficients

In-plane		e-6/°C	Curvat.		(1/m)/°C
alpha_x	=	2.78	delta_x	=	0
alpha_y	=	2.78	delta_y	=	0
alpha_xy	=	0	delta_xy	=	0

Figure 4: Example of sandwich of XN50/Epoxy pre-cured plates and lead with effective CTE near that of silicon; GFRP and lead layers are bonded together with room temperature epoxy.

As examples of this approach, we designed a panel based on XN50A and P120S composite sheets. The thickness of the GFRP sheets was set to 300 microns. They were assumed made of 4 layers (75 microns each) of balanced plain weave fabric (50% total fiber volume content) with ply angles of 0/45/45/0, giving quasi-isotropic in-plane properties. The sandwich designs are illustrated in Figs. 4 and 5.



Laminate engineering constants and expansion coefficients

Laminate : **postbonded P120/Ep and lead sandwich**
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Lay-up : (0a/+45a/-45a/0a/(0b/0c[t=0.467]/0b/0a/+45a/+45a/0a)3) [r

Ply
a P-120S;10/2180/Epoxy;Generic/V_f=50,f_1=50 (1) 75 micron
b generic epoxy bond layer (50 micron)
c Metal;lead

Moduli (GPa)

In-plane			Flexural		
E_x	=	65.98	E^f_x	=	85.17
E_y	=	65.98	E^f_y	=	85.17
G_xy	=	24.90	G^f_xy	=	31.84

Poisson's ratios

nu_xy	=	0.325	nu_yx	=	0.325

Thermal expansion coefficients

In-plane		e-6/°C	Curvat.		(1/m)/°C
alpha_x	=	2.85	delta_x	=	0
alpha_y	=	2.85	delta_y	=	0
alpha_xy	=	0	delta_xy	=	0

Figure 5: Example of sandwich of P120S/Epoxy pre-cured plates and lead with effective CTE near that of silicon; GFRP and lead layers are bonded together with room temperature epoxy.

5.3 Lead Matrix/Graphite Fiber Composite

This approach would consist of building thin sheets of a metal-matrix composite with lead as the matrix material. Such composites have been successfully produced with aluminum, copper, titanium and other metals but not lead. One company has reportedly had some success cold laminating carbon fiber fabrics with lead sheets but it is unlikely that the fiber-matrix "bonding" was good enough to affect the effective CTE. The approach for attempting this lead matrix composite would be a melt casting of lead into either a fabric of a high porosity carbon-carbon mat. Clearly, developing and testing this approach may constitute a substantial R&D project in itself. The option is included here for comparison purposes as it is the lowest mass and volume approach to producing near zero CTE lead composites (since there are only 2 materials: lead for its high RL and graphite fibers for their low CTE and high modulus).

The same two options for graphite fibers were used to design two examples of such composites: XN50A (or P75S) and P120S (or XN85A). Fiber orientations were assumed to be an even mix of 0 and 90 degrees (as would be the case if plain weave fabrics were used). Micro-mechanical analysis was used to predict the effective CTE of the lead matrix composite as a function of the total fiber volume content, and evaluate the total fiber volume content required to achieve a CTE of 2.6ppm/degC. The results are summarized in Fig. 6.

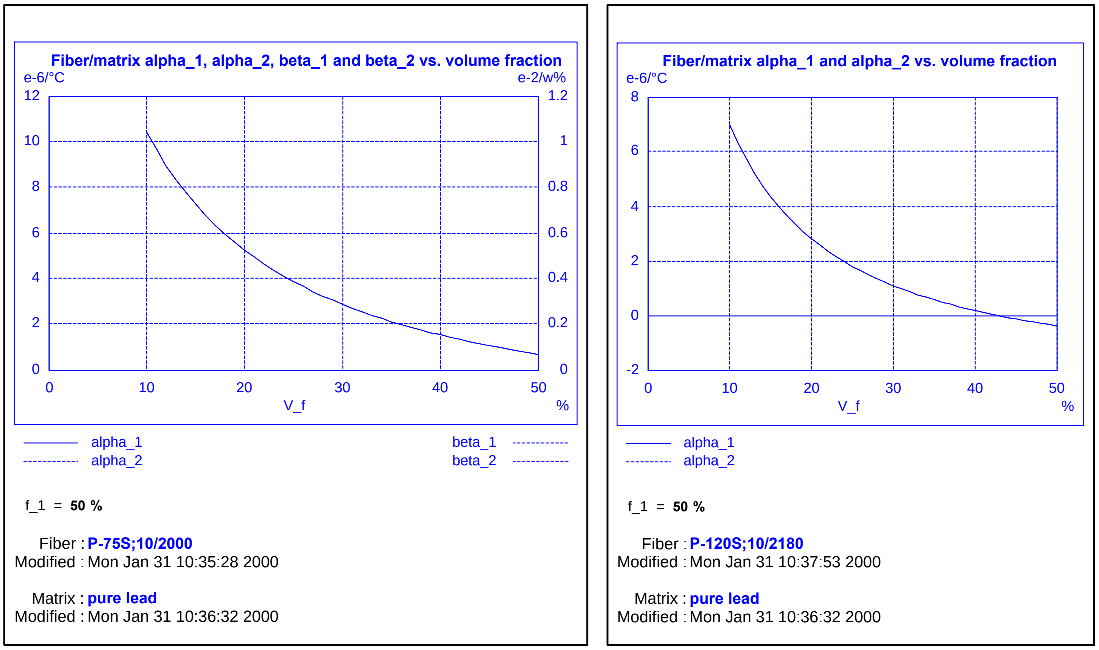


Figure 6: Effective CTE of balanced 0/90 lead matrix composite as a function of total fiber volume content; left side assumes P75S or XN50A fibers, right side assumes P120S or XN85A.

These analyses show that the CTE of the composite will be about 2.6 ppm/degC for a total fiber fraction of 31.5% by volume of XN50A fibers or 21.2% by volume of P120S fibers, in 2D balanced 0/90 arrangement. The composite modulus at those volume fractions would be about 99 GPa with P120S and 92 GPa with XN50A. Those composites would contain 78.8% (for P20S) and 68.5% (for XN50A) lead by volume, so that, neglecting contributions from the carbon fibers, the total thickness for a 25% RL sheets would be 1.78mm with P120S and 2.04mm with XN50A.

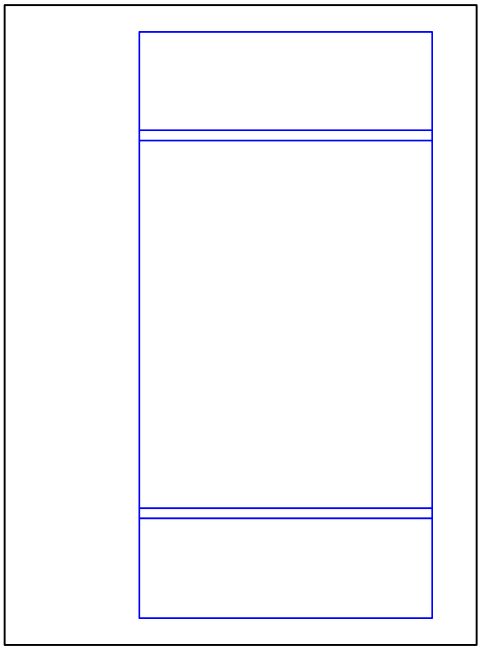
5.4 Invar and Lead Sandwich

This option would consist of few layers of lead and Invar bonded together into sandwich sheets. It was suggested by our Italian collaborators and is included here for comparison. It should be noted that because Invar has a higher CTE (about 1.2 ppm/degC[2]) than 0/90 GFRP, the total added thickness of stabilizing material will be larger, making this the highest weight of the four. However, because Invar has a fairly short radiation length (1.64 cm), the Invar layer contributes a conversion effect and the total thickness of lead can be reduced.

In this case, the thicknesses of the layers can be determined with Eq. (1). Assuming a lead/invar/lead 3-layer sandwich, and a total of 1.4mm of lead, the thickness of invar required is 2.62mm; this is reduced to 1.6mm of Invar and 0.86mm of lead total to bring the total radiation length of the sandwich back to 25%. An ESAComp analysis of that sandwich is shown in Fig. 7.

[2] Invar36 between room temperature and 100degC. Note that the CTE of Invar is higly temperature dependent.

Note that two layers of epoxy were added in the detailed analysis, making the CTE slightly larger than 2.60ppm/degC.



Laminate engineering constants and expansion coe

Laminate : lead/invar/lead sandwich
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Lay-up : (0a[t=0.428]/0b/0c[t=1.598]/0b/0a[t=0.428]) [mm]

Ply
a Metal;lead
b generic epoxy bond layer (50 micron)
c Metal;Invar36

Moduli (GPa)

In-plane			Flexural		
E_x	=	92.96	E^f_x	=	44.42
E_y	=	92.96	E^f_y	=	44.42
G_xy	=	35.75	G^f_xy	=	17.09

Poisson's ratios

nu_xy	=	0.3	nu_yx	=	0.3

Thermal expansion coefficients

In-plane		e-6/°C	Curvat.		(1/m)/°C
alpha_x	=	2.67	delta_x	=	0
alpha_y	=	2.67	delta_y	=	0
alpha_xy	=	0	delta_xy	=	0

Figure 7: A symmetric, 3-layer, 25%RL sandwich of pure lead and Invar 36, bonded with structural epoxy; the effective CTE is close to that of silicon.

6. Summary Table

Design				Lead layers		Stabilizing layers		Resulting Sandwich		
ID	Concept	Stabilizing material	Stacking Sequence	t (mm)	# ply	t (mm)	# ply	t (mm)	Added thickness	Added mass
1	Baseline	Pure lead	Pure lead	1.40	1	-	-	1.40	0%	0%
2	Co-cured lead & GFRP	XN50A GFRP	GFRP/[Pb/GFRP]$_{36}$	0.04	36	0.08	37	4.18	199%	30%
3		P120S GFRP	GFRP/[Pb/GFRP]$_{14}$	0.10	14	0.08	15	2.53	81%	12%
4	Bonded Lead & GFRP	XN50A GFRP	GFRP/[Ep/Pb/Ep/GFRP]$_{10}$	0.14	10	0.30	11	5.70	307%	43%
5		P120S GFRP	GFRP/[Ep/Pb/Ep/GFRP]$_{3}$	0.47	3	0.30	4	2.90	107%	15%
6	Bonded Lead/Invar	Invar	Pb/Ep/Invar/Ep/Pb	0.86	2	1.60	1	2.45	75%	43%
7	Lead matrix MMC	XN50A fibers	Uniform distr. of 0/90 GF in Pb	-	-	-	-	2.04	46%	8%
8		P120S fibers	Uniform distr. of 0/90 GF in Pb	-	-	-	-	1.78	27%	5%

Table 2: summary of example designs of lead based composites with CTE well matched to silicon and about a total RL of about 25%; the last two columns indicate the thickness and mass *increases* for the various designs as compared to the baseline 1.4mm sheet of pure lead.

7. Conclusions

All approaches for reducing the effective CTE of the lead converters can achieve good CTE match with silicon. A metal (lead) matrix composite is the most efficient, leading to the smallest thickness and mass penalty, but is also the most difficult technology to develop. Co-curing thin lead plies and thin graphite epoxy composite layers is also quite effective if using very high modulus fibers but interlaminar shear stresses caused by cooling from cure to room temperature should be examined. Secondary bonding of pre-cured composite sheets and lead sheets allows the use of a smaller number of thicker plies but introduces an additional thickness penalty because of the multiple bonds. Lead/Invar sandwiches require large amounts of Invar leading to a substantial mass penalty.

All preliminary design examples presented in this note were based on specific types of fibers and/or grades of materials; some material properties were based on "generic" materials. Clearly, a logical approach for developing such composites would consist of first selecting the approach, materials, and vendors, then collecting final material property data, and repeating the analyses to refine manufacturing parameters such as fiber volume contents and layer thicknesses. Propotype pieces of those design would then be produced and tested.