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Gamma-ray Large Area Space Telescope (GLAST)

Large Area Telescope (LAT)

Final Report of the GLAST LAT Tracker Anomaly Resolution Team

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DOCUMENT APPROVAL

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CHANGE HISTORY LOG

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1. Introduction

On August 13, the GLAST LAT principal investigator and project manager chartered the Tracker Anomaly Resolution Team (TART) to investigate bias circuit bond delaminations occurring during thermal vacuum tests of flight trays of the LAT Tracker subsystem. The charge to the TART can be found in Appendix A. The team members are identified in Table 1. The team's fact-finding process included a series of telephone conferences with tracker team members at SLAC and INFN Pisa. The team met with INFN Pisa and their tray manufacturing contractor, Plyform, during visit to Pisa on August 30 – September 2. Team member, Jari Drlik, was not able to travel and consulted with the chairman via telephone and email exchanges on particular issues. The table recognizes additional important participants and contributors to the discussions.

Table 1. Anomaly Resolution Team Members

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1.1 Problems

The bias circuit delaminations to be investigated included

- Large scale waves or ridges in the bias circuit covering a large fraction of the tray surface. Observed on both sides - bond to tungsten and bond to face sheet of tray.
- Smaller scale – few centimeter diameter – delaminations only in bond to tungsten.

Other problems identified

- Delamination of tungsten tile to face sheet of tray
- Evidence of incomplete curing of adhesive in an area of a few cm diameter in bond of bias circuit to tungsten.

By way of definition, bubbles in the adhesive layer are also observed. These are defined to be small features on the order of size of a grain of rice that are not considered a problem.

Features larger than 2 – 3 cm in diameter are considered delaminations and have been subjected to remedial action – lancing with a scalpel – to preclude growth in size or interference with silicon ladders mounted above the bias circuit. The advisability of this lancing is of some concern since it involves cutting through a voltage plane in the bias circuit with potential for a short circuit to the grounded tungsten or tray structure.

Additionally, the team was asked to consider techniques to provide a more reliable grounding of the tungsten tiles to the tray structure.

1.2 Abbreviations / Acronyms

EM	Engineering model tracker tower consisting of the full complement of 18 trays but using inactive silicon ladders and non-standard electronic boards (MCMs). This was a thermal – mechanical model
MEK	methyl ethyl ketone
MCM	Multi-chip module. Custom electronic module mounted on two of the sides of a tracker tray
TKR	Tracker subsystem
TVAC	Thermal vacuum test
W	Elemental symbol for tungsten

2. Findings

2.1 Observations

1. Through an unfortunate combination of changes in design and changes in test protocols, the engineering model TKR tower did not uncover the bonding failures that have been discovered in flight component manufacturing. It is not clear if any of the design changes have contributed to the failures or if the EM testing just did not expose the problems. The EM trays received thermal cycles and TVAC cycles only after mounting silicon and electronics boards. It is possible that the delamination problems discovered in flight trays now lay hidden in the EM tower, covered by the silicon. It is also possible that the bonded silicon ladders on the EM stabilized the other bonds and prevented the delaminations observed in testing of flight trays without the silicon payload.

2. As a result of these design changes and new test requirements, the EM program did not adequately verify the design margins in the flight design and bonding processes. The new test requirement for a thermal vacuum bake out at 85 degrees C was not reviewed in terms of mechanical stress impact and material properties. While it exposed bonding weaknesses that might have been exposed in subsequent subsystem or system level testing, the temperature is likely incompatible with bonding adhesive (3M2216 gray) and bond thickness constraints.
3. More aggressive process controls and quality assurance activities are needed in the handling of tray materials and execution of manufacturing processes. Outside of Plyform there appears to be little visibility into the process flow and inspection points that are typical of flight manufacturing process. There also appears to be no formal change control process when modifications to manufacturing processes are made.

2.2 Root Causes

There appear to be three root causes to the delamination problems discovered in flight tray thermal vacuum tests.

2.2.1 Over test

The added test to thermal vacuum bake out the bonded flight trays prior to installation of silicon ladders was ill conceived. The specified maximum temperature of 85 deg C was selected without consideration of the mechanical stresses that temperature placed on the tray and its bonded joints. From the aspect of an environmental test appropriate for a component of the TKR with environmental requirements as specified in LAT-SS-00778 (qualification temperature range –30 to +50 deg C), that temperature represented a significant over test.

However, after the first TVAC failures, the TKR team modified this maximum temperature to a much more reasonable 55 deg C for subsequent trays. When delaminations continued to occur at this temperature, it was reasonable to assume that the tray design or the execution of the tray manufacturing processes did not have adequate margin for meeting the requirements for the TKR subsystem.

2.2.2 Process flaw – bonding surface preparation / protection

Inadequate preparation of the bonding surfaces and inadequate control or prevention of contamination of the surfaces have resulted in weakened bonds that cannot withstand the stresses of the elevated temperature of the TVAC test. This is particularly the case for preparation of the tungsten tiles.

2.2.2.1 Tungsten Surfaces

The original process for tungsten surface preparation consisted of hand sanding with 60 grit aluminum oxide paper and cleaning with MEK or equivalent. This process was used for the EM tower and the first TKR trays that failed during 85C TVAC. In reaction to the failures the surface treatment was modified to aluminum oxide grit blasting at an outside facility. Peel strength tests showed that the grit blast process increased the bond adhesion by about a factor of two. However, significant deformation (warping) of the thin W tiles occurs in this process. This warping creates other problems. Inspection of the grit blasted tiles also shows obvious evidence of contamination in the visible form of fingerprints. Other tiles showed bad water breaks even without visible contamination. It is quite reasonable to assume that the bonds to tungsten to date have the best achievable adhesion only by luck.

2.2.2.2 Contamination from sequential bonding steps

Both surfaces of the tungsten tiles are bonded. This presents significant danger of contamination of the second surface during bonding of the first surface. The first bond attaches the first side of a tile (W1) to the face sheet of a tray. In the Plyform tooling, this process positions and holds the second surface of the tile (W2) against the tool with a vacuum. However, the tool has been prepared with mold release to remove the bonding unit from the tool. Thus the W2 tile surface is in danger of contamination with mold release.

This is particularly a problem for the thin W tiles which have been deformed by grit blasting. The warping of the thin tiles presents difficulty in establishing the vacuum hold of the piece which results in sliding and scraping of the tile against the tool. Consequently, it is believed that the W2 surface of some thin tiles have been contaminated with the mold release used for the W1 bond. This contamination then poisons the bond of the W2 surface to the bias circuit. Inadequate cleaning of the W2 surface prior to the bias circuit bond could distribute the mold release over the entire surface of the tile.

The probability for mold release contamination of the thick W tiles is much less since the thick tiles are not warped by the grit blast process and the alignment and vacuum attachment of these tiles is much easier.

This mold release contamination hypothesis can explain several of the observed phenomena:

- Bias circuit delaminations are observed on the grit blasted thick tiles with much lower frequency than with the thin tiles.
- Adhesion failures over the entire face of a tile in several cases with, at the same time, good adhesion to the 2 mm bond line separating the W tiles.
- Incomplete curing of the 3M2216 material was reported in one instance, indicating relatively gross contamination, possibly from the mold release or from incomplete removal of the MEK used for cleaning.

2.2.2.3 Bias circuit surface preparation

Evidence suggests that the adhesion of the bond to the bias circuit is strong. Gross delamination of the bias circuit to the tray face sheet has only been observed in trays taken to 85C in TVAC. However, good bonding practice to Kapton requires roughening or removing the shine of the Kapton surface. No roughening has been used in bias circuit bonding to date.

2.2.2.4 Bias circuit moisture removal

Kapton absorbs moisture up to about 1% by weight. This moisture presents a potential source of gases that could cause bubbles or delaminations at the elevated temperatures of the TVAC test. Bias circuit bonding preparation included no bake out of the circuit to remove this moisture.

2.2.3 Process flaw – application and compression of adhesives

The development of the bonding processes determined that the best planarity of the bias circuit is achieved with the minimal application of 3M2216 adhesive. The surfaces are merely wetted with a measured amount (10 gm) of adhesive that is distributed with a roller until the appearance of a uniform wetting of the surface is achieved. This process results in planarity well within spec and a bond line thickness of about 50 μm. More adhesive results in thicker bond but degraded planarity.

This bond thickness is somewhat thinner than the general recommendation (75 – 125 μm). The analyses seem to be inconclusive on the strength margins of such a bond – largely due to the complexity of the problem and the lack of needed material properties for an accurate model.

A second concern with the bond thickness is its similarity with the size of non-planarities in the tray face. These variations, coupled with the viscosity of the adhesive and the method by which compression of the joint is applied during cure, present the potential for bridging or adhesive starvation at depressions in the tray surface. The compression is applied by a stiff plate that backs the bias circuit. The viscosity of the adhesive limits its redistribution to equalize the pressure across the face. A similar and potentially worse situation occurs on the bond of the bias circuit to W tiles particularly if the tiles are warped. This bridging could result in poor polymerization of the adhesive and present prime sites of delamination. It should be noted that there is no conclusive evidence that this occurs. A correlation of delamination failure positions with CMM inspection data could perhaps provide this. It’s not clear that sufficient data exists to make this correlation.

3. Recommendations

The team identified the following 12 recommendations. The first 9 recommendations, 3.1 thru 3.9, are expected to provide the greatest benefit to the program and should be implemented.

3.1 Qualification program

Design and execute a tray bonding qualification test which shows that the flight design, after changes, has margin to TKR subsystem qualification environment requirements.

3.2 Tungsten surface preparation

Use the chemical etch process of MIL-HDBK-961B or equivalent to prepare the tungsten surfaces for bonding. The recommended process includes priming with BR-127 to protect the surfaces during storage and transpiration. This priming could cause problems with the grounding of the W tiles to the tray structure. A conducting version of the BR-127 is available from Cytec. It could be considered. A non-primed process could be considered but in that case much greater care must be given to the W surfaces. The water break test should be performed on non-primed W to verify cleanliness.

An example of the steps to prepare the W surfaces and prime them primer should consider the following issues

1. Inspection
   - verify planarity of 100 μm tiles.
   - Surface defects, irregularities
2. Degrease – vapor or ultrasonic with acetone or MEK. Oakite 160 or sodium hydroxide could be used to enhance the subsequent chemical etch.
3. Chemical Etch per MIL HDBK-691B paragraph 5.3.5.1.14 or equivalent. Use deionized water rather than the prescribed distilled water. The etch should remove no more that 5% of the tungsten. This can be checked by weight or thickness measurements on control samples.
4. Prime surface with BR-127 to thickness and cure per manufacturer's recommendation within 8 hours of etch. If the priming is performed at a facility other than the etching, lot sample water break tests should be performed on the material received for priming prior to primer application.
5. Separate tiles with clean Tex Wipe or equivalent and store stacks of tiles in clean, non-contaminating vacuum-sealed bags.
6. T peel verification of lots per process contol recommendation (section 3.7.2) should be performed prior to flight tray bonding.

3.3 Bias Circuit Preparation

Roughen, clean and bake the bias circuits prior to bonding. Procedure steps are:

1. Roughen surface with Scotch Brite pads or 400 grit aluminum oxide paper until sheen is removed. A reference standard bias circuit should be provided as a visual verification.
2. Clean – acetone (MEK) wipe followed by IPA wipe
3. Bake 60 deg C for 12 hours.
4. Clean – acetone (MEK) wipe followed by IPA wipe
5. Wait ~30 minutes for solvents to evaporate
6. Bond

3.4 Tungsten Bonding

Address contamination problems associated with the sequential bonds to tungsten sides. Consider the process steps identified below.

ISSUE: mold release on alignment/bonding tool used in W bond to face sheet can be transferred to the 2nd surface of W tile. This is a particular concern for the thin W tiles where planarity is a potential problem. With the thick tiles, planarity is very good so transfer should not be as great. For thin tiles, use thin sheet of polyethylene between tile and tooling. Holes should be pricked into poly for vacuum chuck action.

1. Remove tiles from storage bags as needed for bonding
2. Clean with Acetone (or MEK) wipe and follow with IPA wipe.
3. Wait ~30 minutes for solvents to evaporate.
4. Bond to face sheet.
5. Cure 1st bond
6. Clean 2nd (exposed) W surface with MEK (need to remove all mold release used in 1st bond). Use only wipes, no abrasion. Must protect the primer.
7. Wait at least 1 hour for MEK evaporation.
8. Apply 3M2216 and bond.

3.5 Preparation of Adhesive

De gas the mixed adhesive before application to surfaces to be bonded:

1. Mix larger quantities than need.
2. Degas mixed adhesive in bell jar. – Pump on mixture until bubbles stop appearing and have broken, release vacuum, then repeat at least one more time.
3. Transfer needed quantity to clean surface for weighing.

3.6 Grounding of Tungsten tiles

The recommended method for the bonding of the tungsten tiles to the tray structure is with a number of stainless steel (or equivalent, eg. silver) wires, the length of the tray, embedded into the adhesive after leveling. This should require no modifications to the tooling but may result in a thicker bond. Wire diameter of ~50 μm is recommended. Two wires per ladder should be sufficient. Wires run orthogonal to ladder. The wires should be solvent wiped (MEK or acetone) before installation in adhesive. The use of the grounding wires will also control bond spacing.

The use of the primer, unless conducting primer is used, could prevent electrical contact with the tungsten tile. A process of preparing and protecting the tungsten surface that does not use primer could be considered.

3.7 Process cleanliness

Implement the manufacturing guidelines and process controls listed below:

3.7.1 General Manufacturing guidelines

1. Smocks and hairnets should be worn in all flight manufacturing activities. The bonding area should be clean, temperature and humidity controlled, free of particulate generating material (eg. cardboard boxes), and an area dedicated to bonding or lay-up operations. No silicone processing, mold release applications, eating, drinking , use of aerosol sprays, and operation of polluting-generating machinery should be permitted there. Personnel access should be limited to as few as necessary. The area should receive routine housekeeping. Laminar flwo in the bonding area is desirable. As a minimum, the area should have adequate ventilation for the venting of solvent vapors that may contaminate the bonding materials. Control of particulates in Plyform tray bonding are is required. Consider use of clean tent. Any pumps used in the manufacturing area should be vented to the outside.
2. All handling of flight materials should be performed with appropriate gloves to avoid surface contamination. In most cases for general handling and personnel protection nitrile gloves are acceptable. However, when using any solvents, eg. MEK or acetone, polyethylene gloves should be used. The polyethylene gloves can be worn over nitrile gloves. MEK and acetone attack nitrile and surfaces being cleaned could be contaminated with nitrile.
3. **Procedure for Solvent Wiping.**
   Wearing appropriate gloves, wipe with successive wiping cloths (Tex Wipe 609 or equivalent), each saturated with solvent, one pass in one direction for each cloth. Repeat until no visible residue remains on the wiping cloth. Be careful not to drag contaminants into bond area from any surrounding area. To minimize solvent evaporation and waste, small cloths are recommended. On the last wipe, remove the solvent with a second clean dry cloth before the solvent evaporates. Wait 30 minutes for the solvent to evaporate before bonding.
4. Adhesive preparation and bonding operations should be performed in clean temperature- and humidity-controlled environment. Temp 23+/-2 deg. Humidity less than 60%. Temperature and humidity of the tray bonding area should be recorded.
5. All abrading operations should be done in a separate room well away from adhesive preparation and bonding activities. These specimens must have the same adhesive thickness as the flight 3M2216 gray bonds. The bond thickness can be controlled using wires.

3.7.2 Process Controls

1. T-Peel test (per Appendix B) for tungsten samples to verify primer and surface prep. Samples should be co-etched with tile material. Lot sample (minimum of three) for each lot. These specimens must have the same adhesive thickness as the flight 3M2216 gray bonds. The bond thickness can be controlled using wires.
2. Adhesive mix sample, for hardness check – correct mix and curing. Aluminum dish, filled uniformly to a depth of ¼ inch minimum. Keep bottom flat during cure. Cure condition/duration should be same as flight sample – 7Day/Room

Temp. Do Shore D hardness test per ASTM D2240-91. 3M2216 specified hardness is 50 – 65. Record and preserve data.

3. Each process step should be given on a process work sheet or log. Quality control inspection should be included for critical steps, such as adhesive mixing, adhesive application, etc.

3.8 Quality assurance and configuration control

More aggressive oversight of manufacturing processes, quality assurance and configuration documentation are needed at Plyform. INFN should have greater visibility into the process work orders, inspection points, and process changes at Plyform. A formal change control process with appropriate approvals should be instituted. All flight hardware must be manufactured with controlled work instructions.

3.9 Non-Use of grit blasted tungsten

Don't attempt to use the 100 µm W tiles that were processed by grit blasting. Rationale: The deformation of the tiles caused by the grit blasting causes spring action in the bonding process which might contribute to bridging and voids.

The 700 µm tiles that have been grit blasted can be used. They should be chemically etched per recommendation 3.1 before use.

3.10 Bond joint compression

Use a compliant sheet between the bias circuit and the compression tool to help distribute the pressure on the joint more uniformly. This will help remove potential bridging or voids in the bond joint which would result in delaminations. Material such as Viton rubber sheet or silicone sheet should be considered. Thickness on the order of 0.5 mm with 10% compressibility for expected loads seems appropriate. Any use of silicone sheet should include bake out at suitably high temperature and duration prior to use to remove any potential of contamination.

3.11 Alternate bond cure protocol

Consider the use of an oven in the first 24 hours of curing of the bond joint. This would speed the polymerization of the adhesive and produce a stronger joint. However, the impact of deformation of the tray must be considered. A cure temperature of 35 deg C seems feasible.

3.12 Examine bonding integrity of the EM tower

Inspect the bonds of bias circuits in the EM at the completion its environmental test program. The EM tower contains the only trays that have seen the qualification temperature range under vacuum. No test article has received more thermal cycles. It has also seen more vacuum cycles. Does this expose more problems? What, if any, are the bond response to –30 C. This is a confidence building recommendation.

This may require disassembly / destruction of some of the EM trays.

4. Verification and Qualification Plan

4.1 Revisions to the manufacturing process

The TART suggests the following test configurations for incrementally modifying the manufacturing processes. The number and sequence of tests in each configuration should be consistent with available material and program priorities. Additional test configurations that provide intermediate results are encouraged and best determined by the Tracker team.

4.1.1 Tungsten tile preparation comparision

Tom Venator will transport a tower worth of tungsten tiles back to NASA/GSFC to be processed in GSFC's plating shop. Plyform is also preparing tungsten in Italy. A comparison of the results of the two sources of etched and primed tile should be performed using T peel strength tests on samples of the 100 μm tiles. Use the ones that show the best strengths. Appendix B identifies the sample size to be used in GSFC etch and prime. All samples will be bonded and tested at Plyform.

4.1.2 Test article for tungsten preparation and grounding

Build a tray implementing the process recommendations on preparation of tungsten and bias circuit. Include the changes necessary to test the grounding of tungsten using wires in the adhesive. Use primed tungsten. Do not include the compliant compression pad in this manufacturing test. Inspect the product for planarity and alignment. Evaluate the grounding success of the primed tungsten tiles. If grounding is not satisfactory, repeat this process except with W tiles that have not been primed.

Test this article in a sequence of TVAC tests that increase the temperature. Inspect the article for delaminations and other flaws between the TVAC tests. The proposed test temperature sequence is +55C, +60C, +65C, +70C. For these tests the duration at temperature does not need to be 24 hours of the standard TVAC test. A soak time of one hour after stabilization of the tray temperature should be sufficient.

4.1.3 Test article for compliant compression pad

Build a tray implementing the process changes as in article above but implement the compliant compression pad in the cure. Inspect the product for planarity and alignment. Test this article in a sequence of TVAC tests that increase the temperature. Inspect the article for delaminations and other flaws between the TVAC tests. The proposed test temperature sequence is +55C, +60C, +65C, +70C. For these tests the duration at temperature does not need to be 24 hours of the standard TVAC test. A soak time of one hour after stabilization of the tray temperature should be sufficient.

4.1.4 Test of alternate bond curing protocol

If the elevated bond cure process is to be tested, a separate test article should be manufactured. The cure temperature should be evaluated in reference to alignment and planarity requirements.

4.2 Qualification Program for the tray panel

After all manufacturing processes have been defined and studied, a flight tray should be manufactured using these released procedures and then subjected to a qualification program. This program should include the standard manufacturing screening tests (eg. ESPI, vibration, TVAC) and add a number of thermal cycles over the tray panel qualification temperature range. Here we are using the GEVS equivalency of thermal cycling to thermal vacuum testing with the appropriate increase (50%) in number of cycles. Also, thermal cycling at ambient pressure adds an additional 5 deg C on min and max temperature range.

The Tracker subsystem environmental test requirements are specified in the LAT Environmental Specification, LAT-SS-00778. Table 2 summarizes the TKR requirements for thermal vacuum testing.

Each completed TKR tower will receive four thermal vacuum cycles at either the qualification/protoflight levels or the acceptance levels.

Additional thermal tests are performed on TKR components prior to passing to the next level of assembly. These tests are summarized in Table 3 along with a proposed qualification test of the design for the tray panel.

At the lowest level of assembly, the tray panel – tray structure with bonded tungsten and bias circuits – receives a workmanship thermal vacuum test at high temperature. This test was originally conducted at 85C and recently changed to 55C. Based on the subsystem qualification and survival requirements the TART believes that executing this test at a maximum of 60C is adequate and would not represent an overtest.

At the next level of assembly – completed tray – four cycles of thermal cycling at ambient pressure are performed as indicated in the table.

Based on these requirements, the TART recommends a tray panel design qualification test consisting of 20 thermal cycles at ambient pressure over the temperature range of –35C to +60C.

Table 2. TKR Subsystem Environmental Test Temperatures - LAT-SS-00778

Test Level	Min Temp (C)	Max Temp (C)
Operating	-15	+30
Acceptance Test	-20	+35
Qual / Protoflight Test	-30	+50
Survival Limits	-30	+50

Table 3. TKR Component Test Temperatures

Test Description	Min Temp (C)	Max Temp (C)
Tray panel thermal vacuum high temperature workmanship test	+25 (RT)	+60 (proposed)
Completed tray assembly - Acceptance thermal cycle (4) at ambient pressure–	-30	+50
Tray panel design qualification test – thermal cycles (20) at ambient pressure	-35 (proposed)	+60 (proposed)

Appendix A. Charge to the Team

To: Neil Johnson
From: Peter Michelson, GLAST/LAT Principal Investigator
Lowell Klaisner, GLAST/LAT Project Manager
Subject: Tracker Anomaly Resolution Team
Date: August 13, 2004

The tracker subsystem has experienced an anomaly during thermal vacuum testing of trays. The bias circuit delaminates from the tray at temperature under vacuum.

Thank you for agreeing to lead a team to resolve this anomaly. In executing this task:

1. Form a small team of experts from within the tracker organization in Italy and the US supplemented by experts outside of the tracker group.
2. Identify the root cause of the anomaly.
3. Propose a plan to resolve the anomaly, qualify the solution, and restart manufacturing in Italy.
4. This plan will be reviewed by Robert Johnson, Ronaldo Bellazzini and Persis Drell. They will vet this plan and recommend action to the LAT Project Manager.

The team will travel to Italy to work closely with the INFN Tracker staff and their subcontractors. The timeline is for the team to be in Italy before the end of August and have the plan to the Project Manager before September 10, 2004.

Appendix B. Plyform T Peel Test Sample Requirements.

To be provided by Sandro Brez.

(ed. Note: We have decided to release the final report without this appendix. The information is for coordinated testing at GSFC and Plyform and relates to Tracker team internal communications. I’m sure they can share this information without including it in this report.)