Final Thermal Design and Thermal Vacuum Testing of the StarBurst Instrument

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The StarBurst Multimessenger Pioneer is a small satellite mission serving as a wide-field gamma-ray observatory designed to capture the initial emissions of short gamma-ray bursts, electromagnetic signatures of neutron star mergers. This paper presents the final thermal design and analysis of the StarBurst Instrument, comprising the bus-to-instrument interface plate, control electronics, and twelve crystal detector units, which form the core of the mission's science capability. The passive thermal control system design requires consideration of restrictive keep-out zones, unknown orbital parameters, and narrow temperature limits of the detectors. Also summarized is the instrument level thermal vacuum cycle test, correlated model refinements, and updated model results. Following successful completion of the instrument test campaign, the hardware was integrated with the spacecraft bus for spacecraft level testing, including additional thermal vacuum testing. The results from the spacecraft level thermal vacuum test will further inform the instrument thermal model, ensuring accurate flight temperature predictions. StarBurst launches as a secondary payload in 2027 and has a mission duration of at least one year.

Acronyms and Nomenclature

α	=	Solar Absorptivity
BOL	=	Beginning of Life
°C	=	Degrees Celsius
CDU	=	Crystal Detector Unit
CEB	=	Central Electronics Box
ΔT	=	Temperature Difference
EOL	=	End of Life
ε	=	Infrared Emissivity
ε*	=	Effective Emissivity
GEVS	=	General Environments Verification Standard
GSE	=	Ground Support Equipment
ICD	=	Interface Control Document
I/O	=	Input/Output
IR	=	Infrared
ISS	=	International Space Station
K	=	Kelvin
LN_2	=	Liquid Nitrogen
LPT	=	Limited Performance Test
MLI	=	Multilayer Insulation
mm	=	Millimeters
MSFC	=	Marshall Space Flight Center
Non-Op	=	Non-Operational
NRL	=	Naval Research Laboratory
Op	=	Operational
PI	=	Principal Investigator
SFL	=	Space Flight Laboratory
SiPM	=	Silicone Photomultiplier
TC	=	Thermocouple
TCS	=	Thermal Control System
TD	=	Thermal Desktop
TIM	=	Thermal Interface Material
T-Vac	=	Thermal Vacuum
UAH	=	University of Alabama in Huntsville
USRA	=	Universities Space Research Association
W	=	Watts
WCC	=	Worst Case Cold
WCH	=	Worst Case Hot
XREF	=	External Reference

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I. Introduction

The Starburst Multimessenger Pioneer project has several institutional partners: Marshall Space Flight Center (MSFC), Naval Research Laboratory (NRL), Space Flight Laboratory (SFL) Missions, University of Alabama in Huntsville (UAH), and Universities Space Research Association (USRA). MSFC is the Principal Investigator (PI) institution and responsible for project management and instrument support electronics. NRL designed and fabricated the instrument sensor head. SFL is responsible for the spacecraft bus development. UAH and USRA are responsible for the instrument flight software, and science operations center, respectively. Figure 1 shows an artist rendering of the spacecraft, indicating the instrument and bus. The rough dimensions of the spacecraft and instrument are 0.8 x 0.8 x 0.9 meters, excluding the solar arrays. The deployed solar arrays from end-to-end measure roughly 3.7 meters.

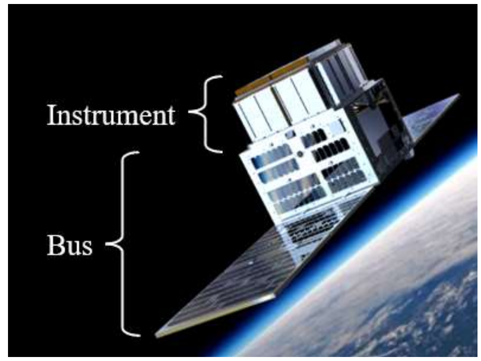

Figure 1. StarBurst artist rendering. (Insulation not shown.)

Included in MSFC duties are the instrument detailed thermal analysis, design, and test, including the key components of the Central Electronics Box (CEB) and Crystal Detector Units (CDU). The instrument components are mounted to a baseplate, which is mounted to the +x side of the spacecraft bus. Figure 2 shows the MSFC Thermal Desktop (TD) Model of the detailed instrument and simplified bus. The multilayer insulation (MLI) is shown as a translucent box and covers the instrument above the baseplate. Primary factors influencing the instrument passive TCS are limited power and volume budget for thermal control, a restrictive keep-out zone impacting insulation placement, narrow temperature limits of critical components, and pre-defined interfaces dictated by an Interface Control Document (ICD).

The StarBurst instrument was tested at MSFC, including bakeout, thermal balance, and thermal vacuum (t-vac) cycle testing in April 2025. These tests verified the thermal performance of the hardware by demonstrating the viability of the design through the operation of the instrument in vacuum at the relevant maximum and minimum temperatures based on analysis predictions plus margins. The test also collected data to inform the thermal model and increase accuracy of flight temperature predictions. Following the instrument level testing at MSFC, the instrument was shipped to SFL and integrated with the spacecraft bus for further testing at the spacecraft level, including a spacecraft level t-vac test.

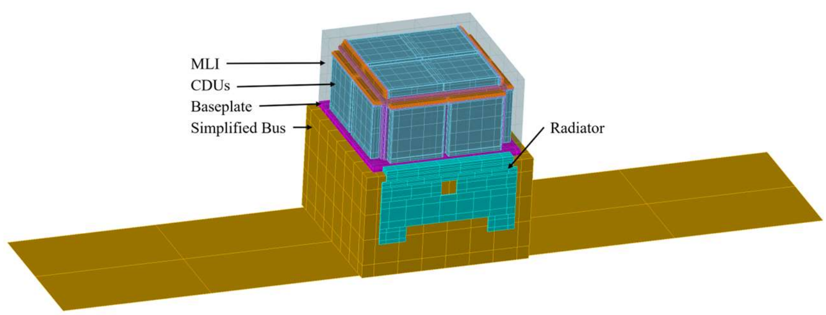

Figure 2. MSFC TD model of detailed instrument and simplified bus.

II. StarBurst Instrument Passive Thermal Control System Design

The StarBurst Thermal Control System (TCS) is passive, excluding heaters, motivated by limited budget, volume, and mass for thermal control, need for simple software control, and required definition of interfaces between partners.

A. Isolation & Insulation

The passive TCS design strategy is to thermally isolate the instrument from the surrounding environment and design the system to dissipate enough heat to cool the instrument when hot and add heat with heaters when cold. As such, titanium standoffs are used to isolate the instrument baseplate from the spacecraft bus. As dictated by the Instrument to Bus ICD, the maximum total thermal conductance between the baseplate and the bus is 2.2 W/K. The total thermal conductance through the standoffs between the bus was calculated and provided by the bus provider.

Isolating the instrument from the bus is beneficial to both the instrument team and bus provider team to reduce the impact of each design on the other.

MLI surrounds the instrument above the baseplate to isolate the instrument from heating effects of the Sun and Earth, and cold sink of space. The MLI is comprised of ten inner layers of double sided aluminized Kapton, an inside layer of aluminized Kapton (inside-facing layer not aluminized) and an outside layer of beta cloth. The beta cloth optical properties are IR emissivity (ε) = 0.88 and solar absorptivity (α) = 0.15. The estimated effective emissivity (ε*) is 0.05. This value was calculated by multiplying the estimated theoretical value by a knockdown factor of ten. A diagram of the MLI coverage is shown in Figure 3. The MLI cannot cover or overhang the edge of the baseplate by more than three mm due to keep-out zone restrictions defined in the ICD. The MLI was designed to fully cover the CDUs with a flap to cover the exposed top of the baseplate. Although the exposed top of the baseplate is a small surface area, it must be covered to prevent increased temperatures due to solar heating.

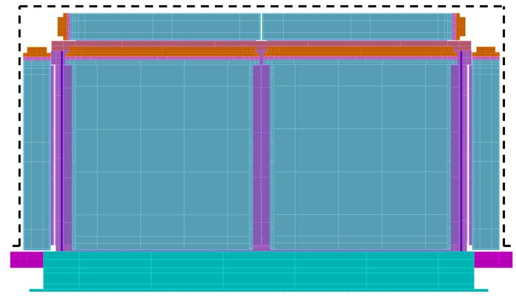

Figure 3. Location of MLI (dashed line) as shown on TD model.

B. Thermal Control Tape

The edge perimeter of the baseplate is exposed directly to the environment. The baseplate coating is iridite chromate with ε = 0.05 and α = 0.304. This results in a α/ε = 6.08, which is not desirable on surfaces that are exposed to the sun because it increases solar heat absorption and causes instrument temperature predictions to rise. The exposed edges of the baseplate were covered with aluminum coated polyimide tape with optical properties of ε = 0.03 and α = 0.086, reducing the α/ε of the exposed edges to 2.87 and preventing the instrument temperature predictions from exceeding maximum limits.

C. CEB Thermal Control

Figure 4 shows the CEB placement in relation to the baseplate and the internal components. Figure 4 a) and b) show the CEB enclosure as translucent. The CEB contains the electronics that control the operation of the science instrument and includes the highest heat dissipating components of the instrument. It is mounted through a lip around the enclosure edge to the baseplate. The lid attaches on the side facing the spacecraft and bolts to the enclosure lip. Within the CEB, two hexMorpho boards each have six slimMorpho daughter cards for a total of twelve slimMorphos. The CEB also contains a power board, input/output (I/O) board, and Xiphos Q8S processor.

The mounting methods for the electronic boards were designed to transfer heat to the CEB enclosure and prevent the electronics from exceeding temperature limits. The hexMorphos are mounted on aluminum planes that conduct heat to the CEB enclosure through Wedgelocks. The power board is mounted directly to a shelf machined into the CEB. The I/O board is mounted through traditional standoffs because it dissipates the least amount of heat. A small riser was machined directly into the CEB enclosure side facing

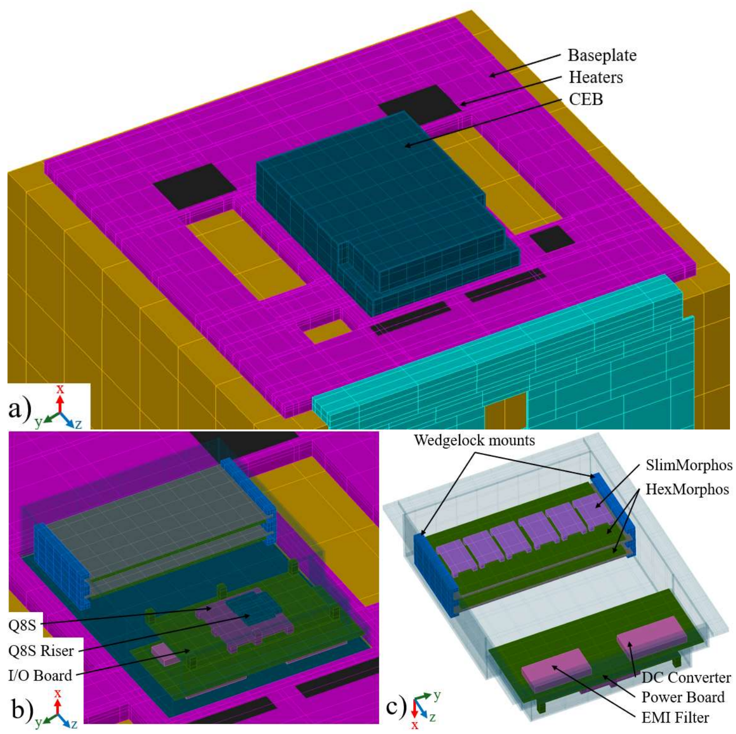

Figure 4: CEB details in TD model. a) Placement within instrument. b) Internal components from +x view. c) Internal components from -x view.

into the instrument to create a smaller gap between the Q8S processor high heat dissipating chips and the enclosure. The thermal interface material (TIM) CoolZorb is used to fill that gap and transfer heat to the enclosure.

A surface treatment with a high ε was selected for additional radiative heat dissipation. The CEB enclosure and lid use blue anodization on the external surfaces with ε = 0.87, and the internal surfaces are iridite chromate.

D. Radiator

The TCS includes a radiator mounted to the side of the baseplate that overhangs one side of the spacecraft to dissipate heat from the instrument, which is designed by the spacecraft bus provider. The radiator is mounted to the baseplate through a highly conductive thermal interface and is also mounted to the side of the bus for stability through thermally isolating standoffs. The total conductance from the radiator to the baseplate is dictated by the ICD as a minimum value of 64 W/K. The radiator has a high-ε, low-α coating with ε = 0.844 and α = 0.091 on the outward facing side and low-ε tape with ε = 0.033 and α = 0.049 on the side facing the bus.

E. Heaters

There are five Kapton heaters on the baseplate with 19.77W combined power controlled by three thermostats on the baseplate. The heater placement can be seen in Figure 4 as the dark gray rectangles. If any one of the three thermostats reaches the 'on' temperature, all heaters turn on. The heater placement and control are determined by the spacecraft bus provider to meet a baseplate temperature requirement. Heat is transferred through an aluminum support structure to the instrument CDUs. There are no additional heaters on the instrument CDUs.

III. Pre-Test Analysis Results

The Thermal Desktop (TD) model shown in previous figures was developed to analyze the instrument temperatures and evaluate the TCS throughout the design process. The instrument was modeled in high fidelity including detailed models of each of the twelve identical CDUs. A CDU subsystem model was developed and referenced into the system model twelve times using the TD External Reference (XREF) feature. The spacecraft bus is modeled in lower fidelity to include the impact of the bus on the instrument but is not used to predict bus component temperatures or determine bus thermal design features. Details to create the bus model were provided by SFL. The spacecraft bus detailed thermal model is maintained by SFL and includes a lower fidelity instrument model.

A. Environments

Worst-case-cold (WCC) and worst-case-hot (WCH) environments were developed to bracket the possible flight environments and include consideration of the component heat dissipation range across operation phases and lifetime, worst case environment parameters, and bus maximum and minimum heat dissipation. Table 1 shows the WCC and WCH heat dissipations and rationale based on if the heat dissipation is nominal or peak and beginning-of-life (BOL) or end-of-life (EOL). The silicone photomultiplier (SiPM) and LT1801 components are located on the electronics boards within each CDU. Table 2 shows the WCC and WCH environment parameters. Both operational (Op) and non-operational (Non-Op) cases were analyzed in the WCC environment.

Table 1. WCC and WCH TD model heat dissipations.

		Heat Dissipation per Component [W]		Rationales	
Component	**Quantity**	**WCC**	**WCH**	**WCC**	**WCH**
HexMorpho Board (each)	2	2.74	2.74	costant: Nominal = Peak, BOL = EOL	
IO Board	1	0.65	1	Nominal, BOL = EOL	Peak, BOL = EOL
SiPM (each)	12	0.014	0.09	Nominal = Peak, BOL	Nominal = Peak, EOL
LT1801 (each)	12	0.161	0.161	costant: Nominal = Peak, BOL = EOL	
Power Board - 30V Converter	1	0.91	1.62	Nominal = Peak, BOL	Nominal = Peak, EOL
Power Board - 5V Converter	1	4.33	4.89	Nominal, BOL = EOL	Peak, BOL = EOL
Power Board - EMI filter	1	0.20	0.26	Nominal, BOL	Peak, EOL
Power Board +/-5V Converter	1	1.29	1.29	costant: Nominal = Peak, BOL = EOL	
Q8S Board	1	3.33	6.5	Nominal, BOL = EOL	Peak, BOL = EOL
SlimMorpho Board (each)	12	0.14	0.14	costant: Nominal = Peak, BOL = EOL	
Total Instrument power		**19.97**	**25.73**		
Bus Power	1	29.97	37.37	SFL provided	SFL provided

Table 2. WCC and WCH TD model environment parameters.

Case	Beta Angle [°]	Solar Flux [W/m^2]	Altitude [km]	Albedo	Planetshine [W/m2]	Orientation	Heaters
WCH	67	1414	545	0.36	242	tilted 20° to sun	on - not used
WCC - Op	0	1322	545	0.24	226	nominal	on - not used
WCC - Non-Op	0	1322	545	0.24	226	nominal	on

B. Initial Temperature Predictions

Initial temperature predictions of the instrument were calculated using the above parameters. Both steady state and transient cases were analyzed for each environment. The transient cases assume initial conditions of steady state and simulate twelve Earth orbits. The temperature and rate of change limits along with the transient results are summarized in Table 3. The crystals, inside the CDUs, have a maximum temperature rate of change limit to prevent stress and potential cracking of the crystals due to rapid temperature change. The rate of change limit levied on the baseplate was initially established as a perceived design solution based on the assumption that if the baseplate is controlled to not exceed a temperature rate of change of 10 °C/hour, then the CDUs and crystals also will not exceed the limit.

A minimum margin of 10°C on all temperature predictions is desired. The CDU SiPMs and crystals both have less than 10°C but more than 5°C margin to the established maximum operational limit of 30°C.

Table 3. Instrument component temperature limits and initial predictions.

		Limits				Predictions					
		Op		Non-Op		WCH		WCC - Op		WCC - Non-Op	
	Component	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**
	Baseplate*	40	-30	45	-30	23.68	15.42	-2.45	-8.28	-13.60	-18.15
CDU Temps [°C]	Crystals	30	-25	45	-30	22.27	18.62	-4.24	-6.13	-14.50	-16.32
	SiPM	30	-25	45	-30	22.17	19.29	-4.79	-4.84	-15.18	-15.29
CEB Temps [°C]	Q8S	60	-40	60	-40	30.28	26.40	2.04	-1.22	-14.72	-15.95
	Power Board	125	-55	125	-55	29.87	23.30	4.09	-3.04	-14.67	-16.30
	I/O Board	80	-40	80	-40	33.61	31.73	4.67	2.55	-14.78	-15.83
	DC Converter - 5V	125	-55	125	-55	44.31	44.13	17.02	15.78	-14.84	-16.09
	EMI Filter	125	-55	125	-55	26.46	26.32	0.64	-0.56	-14.87	-16.07
	SlimMorphos	60	-40	60	-40	38.47	34.87	13.07	8.65	-14.50	-15.38
	HexMorphos	70	-40	70	-40	32.36	30.42	6.37	3.63	-14.42	-15.44
Max Rate of Change [°C/hr]	Baseplate	10		10		0.72		6.72		6.72	
	Crystals	10		10		0.01		0.07		0.07	
Heater Duty Cycle [%]		80		80		0		0		0.14	

	> 10 °C margin
	5 to 10 °C margin
	0 to 5 °C margin
	outside limits

IV. Instrument Thermal Vacuum Cycle Test

The instrument was tested at MSFC in building 4619 ET20 test facilities, using chamber V15 which has a twelve-foot diameter. The StarBurst instrument is shown in the test set-up configuration in Figure 5. The instrument baseplate has a footprint roughly 0.7 x 0.7 meters, and the bottom of the baseplate to the top of the upper CDUs measures roughly 0.35 meters. The baseplate was set upon four Teflon standoffs on two sawhorses on the test chamber platform grate. The chamber includes a liquid nitrogen (LN_2) shroud for cooling, and six zones of IR lamps were affixed to stands surrounding the instrument for heating. Forty-one type-T external thermocouples (TCs) were attached with aluminum tape. Temperature sensors internal to the instrument that will be used to collect data during flight were also recorded. CDU flight temperature sensors include one on each enclosure and SiPM board internal to each CDU. Temperature sensors within the CEB include two on each hexMorpho, five sensors for components on the I/O and Power boards, and two on the Q8S.

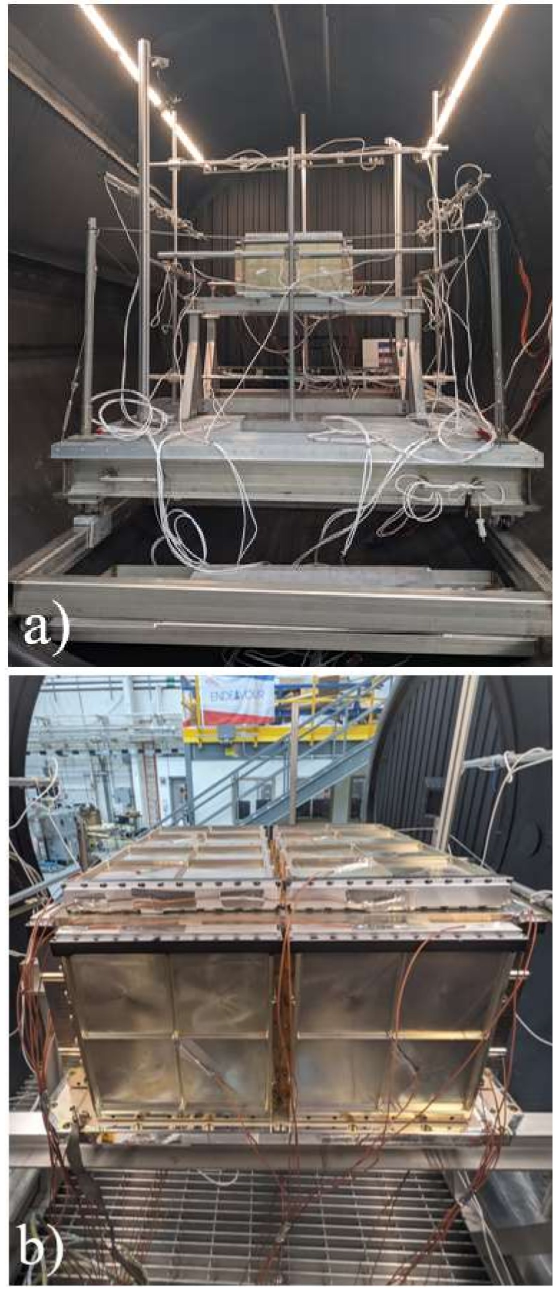

Figure 5. StarBurst instrument in V15 chamber. a) View into V15. b) View out of V15.

A. Test Plan

The General Environments Verification Standard (GEVS) [1] was referenced, which recommends four cycles with twelve-hour plateau dwells for instrument level t-vac cycles. Because no t-vac cycles were performed on the CDUs at the component level before integrating with the instrument and only one cycle is planned for the spacecraft level t-vac test, the instrument team made the decision to increase the number of t-vac cycles for instrument level testing to eight cycles total: four cycles with at least twelve hour plateaus, and four additional risk-reduction cycles with at least six hour plateaus. The first cycle comprises survival and thermal balance plateaus for both hot and cold, and the remaining cycles are operational. Bakeout, cold thermal balance, hot thermal balance, cold-start, hot-start, and calibration steps to collect data at several steady-state temperatures were all included in the test plan. The hot start and cold start were planned twice each, at the voltage corners of 33V during cycle two and 23V during cycle three. Cycle one and cycle four through eight used a nominal operational voltage of 28V. A limited performance test (LPT) was performed during initial and final check outs, and at the beginning and end of each operational plateau.

A summary of test parameters is listed below. The control temp refers to the temperatures used to indicate if the test temperatures have been achieved:

- Pressure: < $1x10^{-5}$ torr
- Survival / bakeout plateaus
    - Dwell time: 24 hrs for bakeout/hot survival, 12 hrs for cold survival
    - Hot: +45°C +0/-2°C
    - Cold: -30°C +2/-0°C
    - Control temp: CDU housing average
    - Instrument power: OFF

- Thermal balance plateaus
  - Steady state: <0.01°C/hr goal or at discretion of thermal engineer depending on time limitations
  - Hot: +22°C ±2°C
  - Cold: -20 ±2°C
  - Control temps: all TCs
  - Instrument power: ON steady
- Operational temperature plateaus
  - Dwell time: 12 hrs for cycles two through four, 6 hrs for cycles five through eight
  - Hot: +30°C +0/-2°C
  - Cold: -25°C +2/-0°C
  - Control temp: CDU internal (SiPM) average
  - Instrument power: ON, including limited performance test (LPT)

The planned test profile is shown in Figure 6.

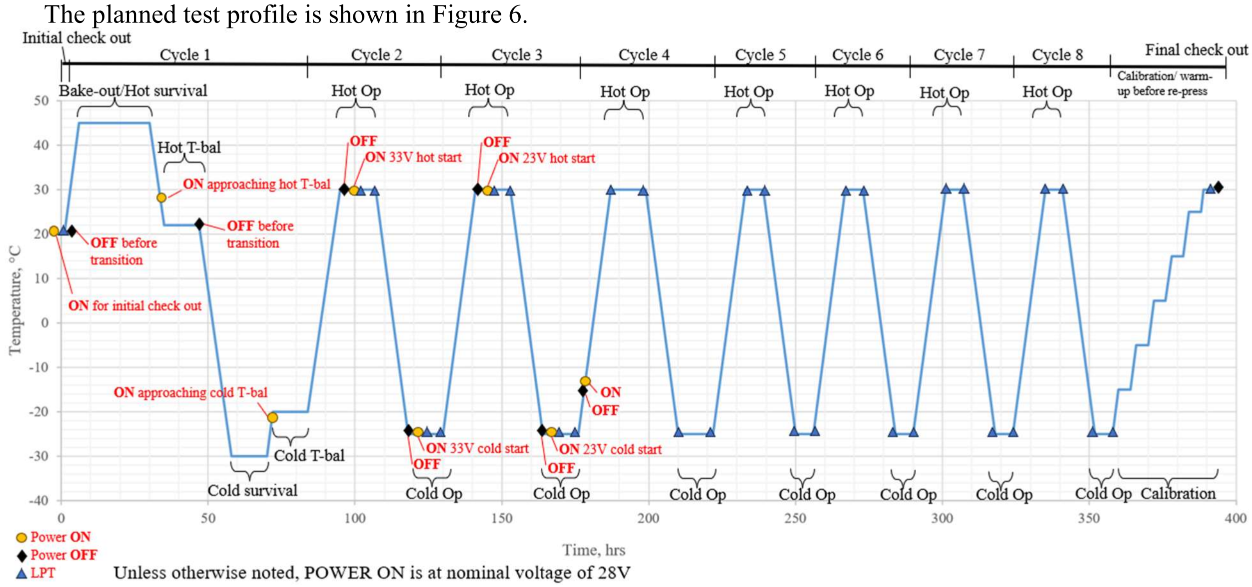

Figure 6. Planned t-vac cycle test profile.

B. As-Run Test Plan

The as-run test profile is slightly different than the planned test profile. Hot survival, cold survival, hot thermal balance and cold thermal balance were achieved. In total seven full cycles were completed and an additional hot plateau. The final cold cycle was not performed due to time limitations. The instrument calibration steps were not performed because the instrument science team determined that the data collected during transition periods between plateaus was adequate to calibrate the instrument.

Figure 7 shows an overlay of the planned and as-run test profiles. During the transition from cold plateau two to hot plateau tree, an anomaly occurred in which the Q8S processor seemingly spontaneously rebooted. Because this occurred during a night shift, the team reset the software and paused the test, holding the instrument at room temperature so that project management could be consulted and agree on a plan forward before further action was taken. The instrument continued to operate nominally after the software reset and the test continued as the team investigated the issue. Because the anomaly occurred during a transition, the next cold-to-hot plateau transition was performed by following the exact timing of changing lamp settings as recorded during the previous transition to recreate the temperature rate-of-change during which the anomaly occurred. The hot start and cold start at 33V were also repeated to determine if the voltage settings are related to the anomaly. The anomaly did not occur again during the transition recreation. The anomaly did occur twice more, during a cold plateau and again during a cold-to-hot transition. Because it occurred at three different temperatures and three different temperature rates-of-change, thermal was ruled out as a cause. The t-vac test is also the first time that the instrument was operated continuously for multiple days and so tested not only thermal performance but long-term instrument operation.

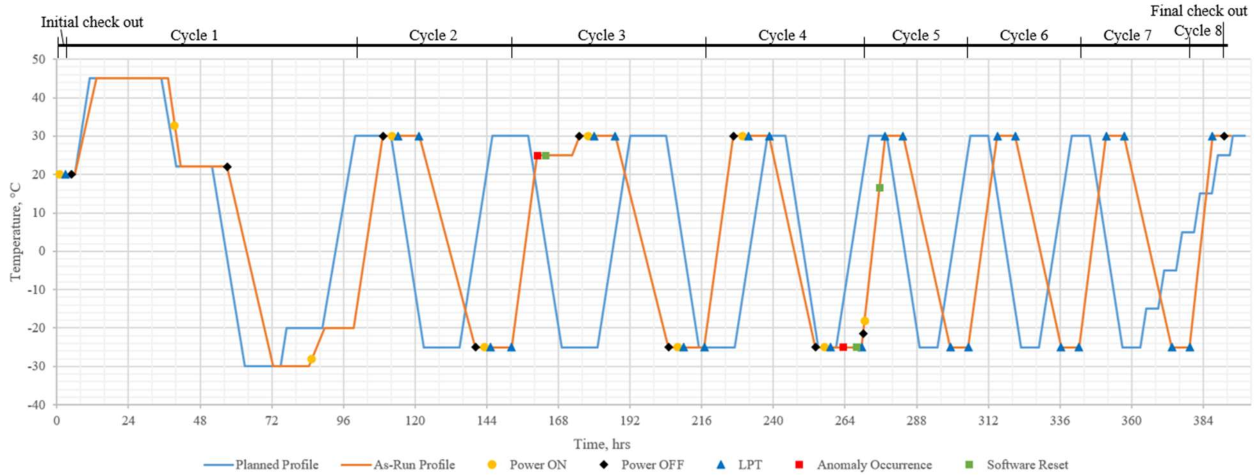

Figure 7. Planned (blue) and as-run (orange) t-vac cycle test profiles.

V. Thermal Model Correlation

A. Model Correlation Data

A temperature rate-of-change <0.1°C/hr was achieved for both hot and cold thermal balance and these data were used for comparison to steady state model data to make updates and increase accuracy of the thermal model. A TD test model was created for correlation and does not include the MLI nor spacecraft bus components. The chamber geometry was modeled as a boundary condition and boundary nodes referencing test recorded temperatures were used to represent the sawhorse. The hot thermal balance correlation compared temperatures at a total of sixty locations, and the cold thermal balance correlation compared temperatures at fifty-nine locations due to the loss of one external TC before the cold thermal balance was reached.

Figure 8 shows the histogram plots of the temperature difference (ΔT) between corresponding temperatures compared for each thermal balance after model updates. The model correlation goal was all temperature comparisons within 3°C which was achieved excluding one outlier. The outlier for both hot and cold thermal balance was an external TC attached to the baseplate above the point of contact with the sawhorse. Because the test temperature was colder than the model temperature in both cases, it is theorized that the TC tape was not well adhered to the hardware, resulting in a slight gap between the TC and baseplate. This TC was also out-of-family compared to additional TCs on the baseplate in close range. This is not on a component with stringent temperature requirements and was accepted as anomalous.

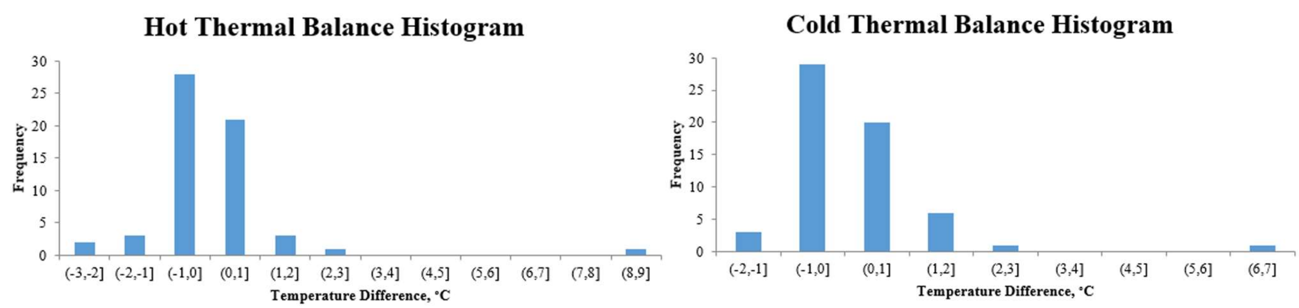

Figure 8. Hot and cold thermal balance histograms.

B. Model Updates

1. Test Environment

The first changes made to the model to match test data were to the boundary conditions. The test ground support equipment (GSE) including lamp stands, cables, sawhorses, and platforms were not modeled as geometry in the test model. Although the shroud temperatures remained near LN_2 temperatures, the surrounding equipment reached higher temperatures, impacting the overall sink temperature. For both hot and cold cases, the boundary temperature and thermal contacts to the sawhorse boundary temperatures were adjusted first to match the model temperatures of the external surfaces of the instrument (CDU outer enclosures, CDU external SiPM trays, CEB lid, and baseplate) to the test data. Then, adjustments were made to the internal components (CEB and CDU internals) to match data, with adjustments made to the boundary conditions as needed to bring all model temperatures within 3°C of test temperatures.

2. *Power Board*

The precise component locations in the model were out-of-date, and so the EMI filter and DC Converter locations were updated for accuracy. The DC2 and DC3 components, which are mounted on the opposite side of the board, were updated to be modeled with explicit geometry. Before test, the DC2 and DC3 heat dissipations were smeared across the power board, and so this update models the individual heat dissipations applied to the component geometry.

The thermal contacts from the power board components to board, and the board to the CEB enclosure were also adjusted. These changes resulted in closer temperature match between the model and sensor locations on the power board.

3. *HexMorphos*

The hexMorpho temperature sensors near the center of each hexMorpho board were hotter in test than in the unchanged model. Before test, besides the slimMorpho daughter boards, the hexMorpho component heat dissipations were smeared across each board. This sensor location is directly next to the highest heat dissipating chip on the board, the U6. Therefore, the U6 geometry and individual heat dissipation was added to the model for both hexMorphos, which decreased the temperature discrepancy.

Each hexMorpho board is fastened to an aluminum mounting plane that is connected to the CEB enclosure through wedgelocks. A knockdown factor of 50% was added to decrease the calculated heat transfer between the wedgelocks and CEB enclosure, and the contacts between the hexMorphos and their corresponding mounting planes were also reduced to increase model hexMorpho temperatures at the sensor location to better match test data.

4. *CEB Enclosure*

The optical properties of the CEB enclosure were updated because the internal surfaces of the enclosure were incorrectly modeled with optical properties of blue anodized aluminum and the hardware internal surfaces are iridite chromate. Only the outside surfaces of the CEB enclosure and lid are blue anodized. The contacts between the lid to enclosure and the enclosure to the baseplate were also updated. These contacts were originally calculated with a knockdown factor added to conservatively estimate the heat transferred to the baseplate, however this was found to be too conservative, and the values were changed to the originally calculated values without a knockdown factor.

5. *Heat Dissipations*

The heat dissipations of the electronics were also updated with values recorded during the test. These are the updated BOL values for updated flight predictions, however the previous estimates for EOL are still used.

C. Updated Temperature Predictions

After the above changes were made to the flight model, updated flight predictions were calculated using the same WCC and WCH environments summarized in Table 2. Table 4 shows the updated flight temperature predictions. Notably, the CDU temperatures decreased, increasing margin on the crystal and SiPM temperature predictions. The slimMorphos and hexMorphos predicted temperatures have also increased due to increasing the fidelity of the hexMorpho board and decreasing the thermal contact from the hexMorphos to the CEB, reducing heat transfer away from the boards, however both still maintain a margin greater than 10°C in the WCH case. The largest difference after model updates is the predicted temperatures of the DC converter, which have decreased due to the updates made to the power board and conduction path from the DC converter through the power board to the CEB enclosure. The power board and EMI temperature predictions have also decreased, although not as significantly.

Table 4. Instrument component temperature limits and updated flight predictions.

		Limits				Predictions					
		Op		Non-Op		WCH		WCC - Op		WCC - Non-Op	
	Component	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**
	Baseplate*	40	-30	45	-30	22.42	14.40	-3.45	-9.13	-14.41	-18.91
CDU Temps [°C]	Crystals	30	-25	45	-30	20.95	17.45	-5.33	-7.10	-15.35	-17.14
	SiPM	30	-25	45	-30	20.77	17.94	-5.89	-6.01	-16.09	-16.21
CEB Temps [°C]	Q8S	60	-40	60	-40	28.87	24.93	0.99	-2.35	-15.52	-16.82
	Power Board	125	-55	125	-55	25.40	21.66	0.49	-4.27	-15.49	-17.14
	I/O Board	80	-40	80	-40	32.32	30.35	3.71	1.52	-15.58	-16.70
	DC Converter - 5V	125	-55	125	-55	26.20	26.01	1.08	-0.42	-15.55	-17.10
	EMI Filter	125	-55	125	-55	22.42	22.27	-2.28	-3.76	-15.56	-17.08
	SlimMorphos	60	-40	60	-40	43.88	39.21	19.00	13.66	-15.36	-16.19
	HexMorphos	70	-40	70	-40	40.80	34.99	15.34	8.85	-15.31	-16.24
Max Rate of Change [°C/hr]	Baseplate	10		10		0.48		6.48		6.72	
	Crystals	10		10		0.01		0.07		0.07	
Heater Duty Cycle [%]		80		80		0		0		0.14	

	> 10 °C margin
	5 to 10 °C margin
	0 to 5 °C margin
	outside limits

D. Forward Work

The StarBurst spacecraft level assembly including MLI is to undergo additional t-vac testing by the bus provider. This test will provide additional data to further adjust the thermal model. Points of interest relating to the instrument thermal control that were not included in the instrument level test include heater operation, radiator contact and performance, MLI performance, and the thermal interface between the baseplate and bus.

VI. Lessons Learned

Throughout acting as lead thermal engineering for the StarBurst instrument, including through earlier design and analysis cycles in addition to flight hardware testing, many lessons were learned. Key lessons are listed below.

- Understand the rationale behind thermal related requirements and limits. There are requirements for both the baseplate temperature and temperature rate of change. After joining the project and requesting more information on these requirements, it was learned that these are not real limits that will cause the hardware to break and are more perceived design solutions than limits. Also, the CDUs initially were estimated to have a lower high temperature limit of 25°C, instead of 30°C. Upon requesting more information and the rationale behind these temperatures, it was revealed that these components could operate at a higher temperature with little impact on performance and the limit was increased.
- Understand previous testing done on the hardware and/or previous iterations of the hardware. Many projects use at least some components that are iterated from previous designs that may even have flight heritage. The StarBurst CDUs and other components are based on an experiment on the outside of the International Space Station (ISS) called Glowbug. The Glowbug flight data was used to develop more realistic worst case heat dissipations of some components due to radiation degradation, which allow for more accurate flight temperature predictions to reference to design a TCS.
- Check templates against the flight hardware if possible. The thermal tape on the baseplate was cut according to drawing specifications. There was one minor difference in the cut tape compared to the flight hardware, which was easily patched with additional tape, however this could have been avoided if the tape templates were checked against the hardware before cutting the tape for installation. The MLI templates were fitted on the flight hardware and changes were made to the size to ensure the appropriate fit.
- Ensure consistent labeling of components between teams and partners. There are twelve CDUs mounted on the instrument and two flight spares. The labels designated by the CDU designers were different than those designated by the science team, which were both different than the TD submodel names. A

translation chart was needed during testing to ensure the data was recorded appropriately and this could have easily been avoided by establishing a consistent naming convention early in the project.

- Alter the environment of the test facility as little as possible. The opening of large high-bay doors in the test area caused spikes in the temperatures recorded on the hardware in the chamber despite the chamber shroud and lamp heating being used to control the instrument environment. This was the case for other tests in the same test area, and it was requested to only open the door part-way when absolutely necessary, which helped to mitigate the issue.
- Ensure the full test team, not just thermal engineers, are aware of the test plan and operations, and communicate any unplanned instrument operations to the full test team. Unplanned instrument re-starts were performed to troubleshoot data collection. Variations in the temperature data were noticed, and the cause was unclear before learning of the unplanned operations.
- Prepare guidelines for off-nominal situations. 24/7 testing requires a team of engineers that must quickly come up to speed on the hardware being tested. Having clear instructions for off-nominal situations, such as power outages, or anomalous instrument operation, will instill more confidence in the test team and ensure that hardware is protected.

VII. Conclusion

The StarBurst instrument level t-vac test collected valuable data while demonstrating the continuous long-term operation of the instrument in the relevant vacuum environment. The t-vac test included four cycles with at least twelve-hour plateaus and an additional three and a half risk-reduction cycles with at least six-hour plateaus. Bakeout/hot survival, cold survival, hot start, cold start, hot thermal balance, and cold thermal balance were also performed. Both hot and cold thermal balance reached a temperature rate-of-change of <0.1°C/hr and data from these points were used to compare to steady state TD model predictions. Changes were made to the thermal model based on data correlation, resulting in increased accuracy and confidence in flight temperature predictions. The instrument has been integrated with the spacecraft and additional t-vac testing will occur at the spacecraft level. Data from this test will be used to further increase instrument model accuracy.

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