Final Thermal Design and Thermal Vacuum Testing of the StarBurst Instrument

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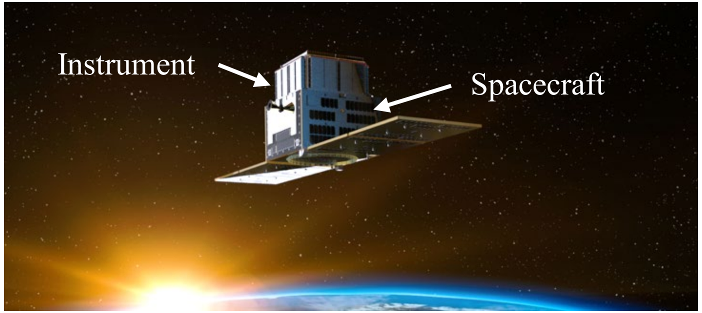
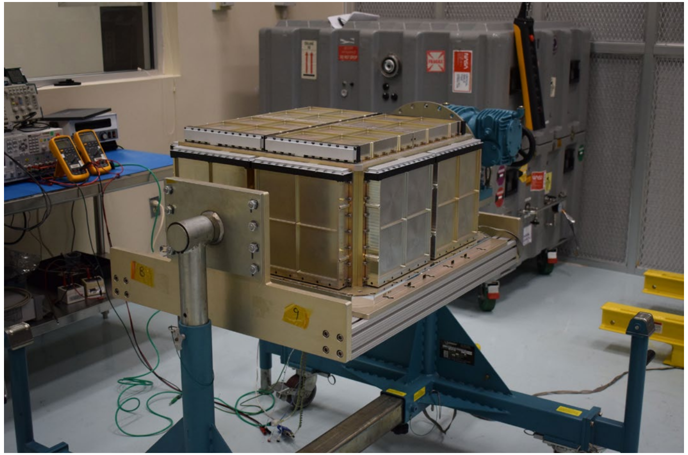
About StarBurst

- **The StarBurst Multimessenger Pioneer** is a highly sensitive and wide field gamma-ray monitor designed to detect the prompt emission of short gamma-ray bursts (SGRBs), a key EM signature of neutron star mergers.
- The StarBurst instrument consists of 12 Crystal Detector Units (CDUs) to detect these gamma-rays, and associated electronics.
- StarBurst Partnership Roles:
  - **NASA Marshall Space Flight Center (MSFC):** Principal Investigator institution and overall project management
  - **Naval Research Lab (NRL):** StarBurst instrument design and fabrication
  - **University of Alabama Huntsville (UAH):** Instrument flight software
  - **University Space Research Alliance (USRA):** Science operations center
  - **University of Toronto Institute for Aerospace Studies (UTIAS) Space Flight Lab (SFL):** Spacecraft bus and mission operations center



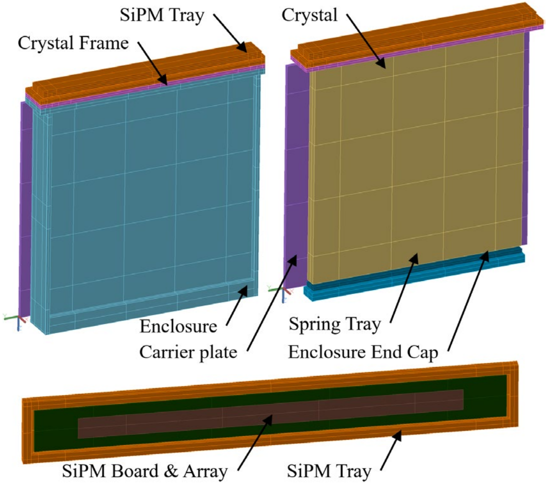
https://science.nasa.gov/mission/starburst/



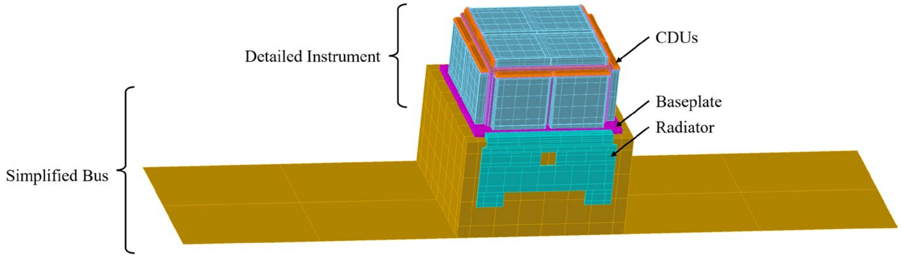
StarBurst Instrument at MSFC/4487/SLTF

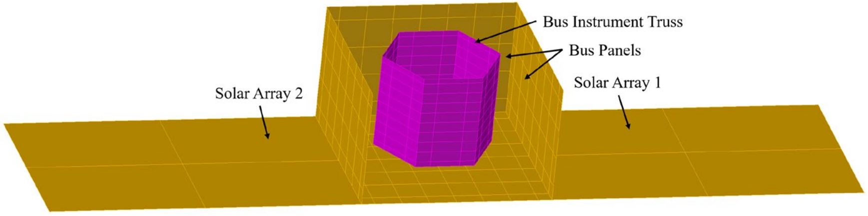
StarBurst Instrument Thermal Model

- The MSFC thermal model includes a detailed instrument and simplified bus components for instrument thermal design and analysis.
  - A detailed CDU model, including internal crystals and electronics, is x-reffed into the instrument model twelve times.
  - The detailed Central Electronics Box (CEB) includes all additional instrument electronics.
    - Individual circuit boards are modeled.
    - Highest heat dissipating components are also modeled on circuit boards.
    - Heat from lower heat dissipating components on circuit boards are applied as an additional heat load evenly distributed across each board.
  - The detailed baseplate and baseplate heaters are included.
  - Radiator parameters were provided by SFL to include a detailed radiator in the instrument model.
  - The bus geometry is greatly simplified.
    - The internal instrument truss structure to which electronics are mouned is modeled.
    - The total bus heat dissipation is evenly distributed across the internal truss.
- The SFL thermal model includes a detailed bus and simplified instrument for spacecraft thermal design and analysis.



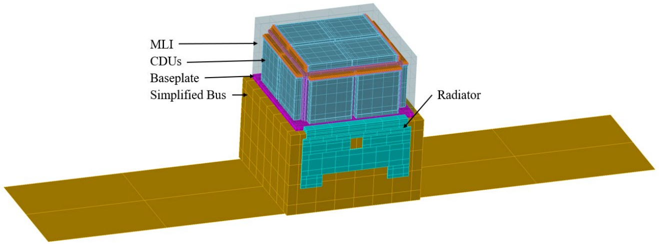
CDU Model Details.

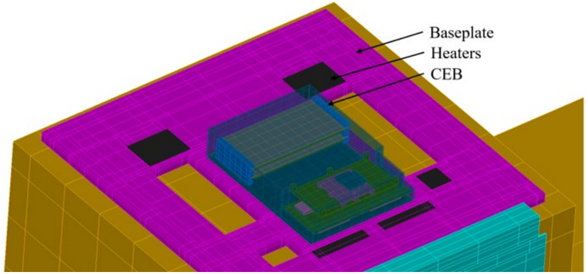


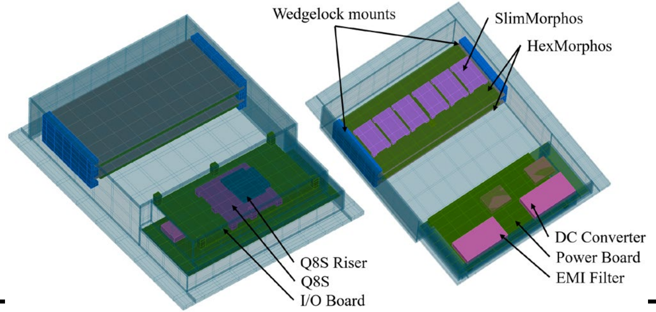


StarBurst Passive Thermal Control

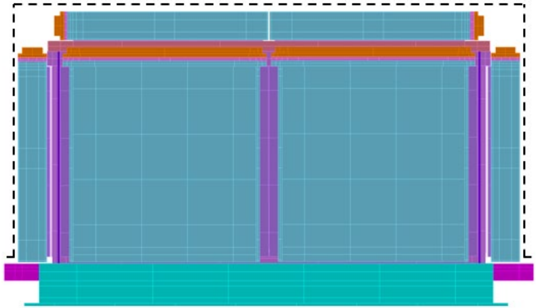
- Multilayer Insulation (MLI)
  - 10 internal layers of aluminized Kapton
  - Outer layer of beta cloth
  - e* = 0.05 (knockdown factor of 10 on theoretical calculation)
  - Covers top of baseplate and CDUs but not edge of baseplate
- Isolation between baseplate and bus
  - Titanium standoffs designed by bus provider
  - Thermal contact between baseplate and bus calculated by bus provider and maintained in Interface Control Document (ICD)
- Survival heaters
  - 5 heaters on baseplate controlled by 3 RTDs
  - Total power = 19.77 W
  - “owned” by bus provider to achieve requirement of maintaining baseplate temperature
- Tape
  - Al coated polyimide tape used on exposed edges of baseplate to decrease a/e (baseplate is Alodine)
- CEB thermal control
  - Enclosure is blue anodized with high emissivity
  - High thermal contact between circuit boards and CEB enclosure
    - HexMorpho boards mounted through Wedgelocks
    - Power board edges mounted to enclosure shelf (not on standoff ‘legs’)
    - CoolZorb between Xiphos Q8S processor and enclosure riser
- Radiator
  - Designed and provided by bus provider
  - Thermal contact between radiator and baseplate calculated by bus provider and maintained in ICD



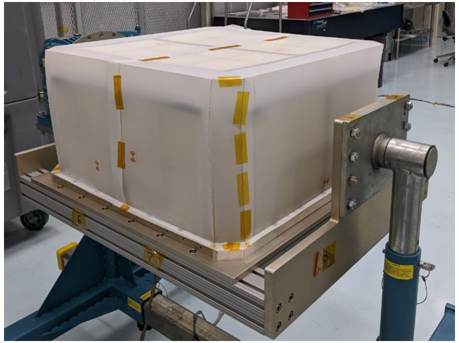




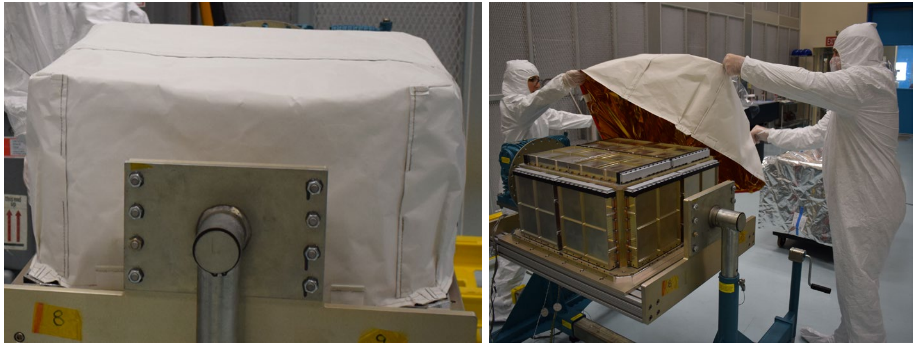
StarBurst Passive Thermal Control



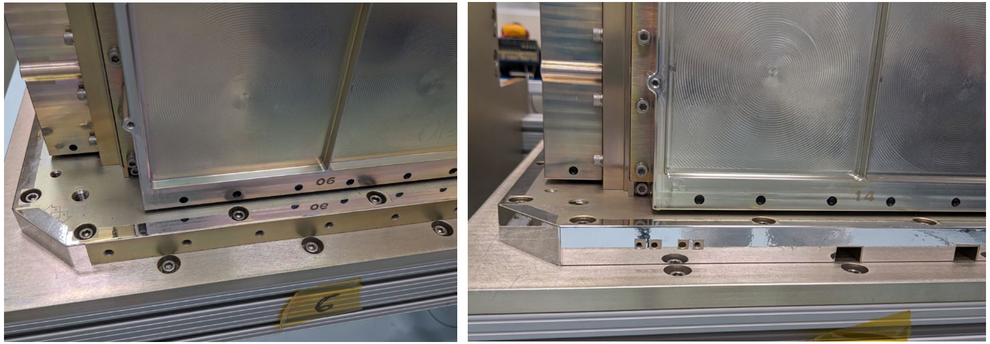
MLI coverage diagram.



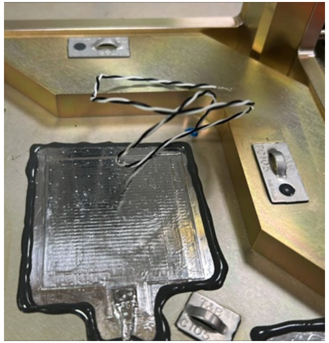
MLI template fit check.



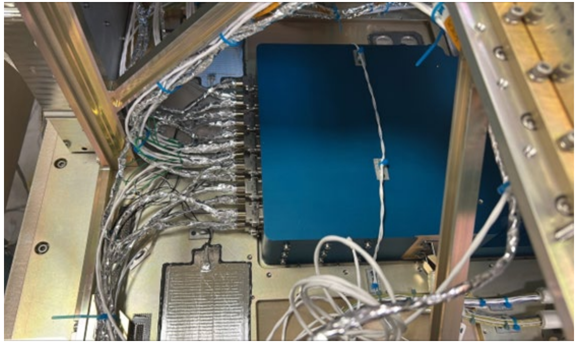
MLI flight blanket fit check.



Thermal control tape on baseplate edges besides radiator attachment edge.



Heater and RTD.



CEB mid harness install.

Thermal Environments & Heat Dissipation

- The worst-case-hot (WCH) and worst-case-cold (WCC) conditions were determined by considering environmental parameters, beginning-of-life (BOL) vs. (end-of-life) EOL operation, and nominal vs. peak heat dissipations.
- Environments
  - The spacecraft will orbit through a range of beta angles throughout the mission.
  - There is a tilt requirement that the spacecraft must operate with the instrument tilted 20° toward the sun.
- Heat dissipations
  - BOL values were verified during thermal vacuum testing.
  - EOL values are based on expected radiation exposure to electronics.

		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	0.090	0.014	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		**20.88**	**24.82**		
Bus Power	1	29.97	37.37	SFL provided	SFL provided

Case	Beta Angle [°]	Solar Flux [W/m²]	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

Pre-T-Vac Model Results

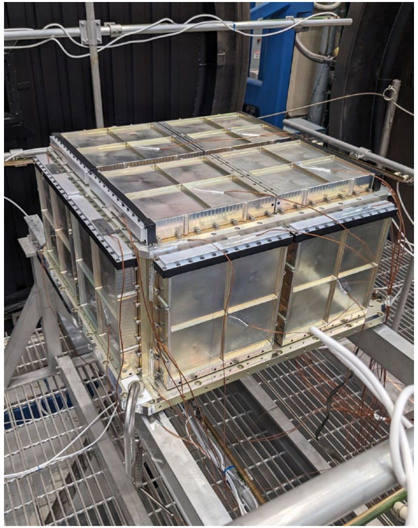
- The WCH environment is predicted to cause crystal and SiPM temperatures with less than 10 °C margin.
- The WCC environment is not predicted to cause any temperature exceedances within the instrument.

Green	> 10 °C margin
Yellow	5 to 10 °C margin
Light orange	0 to 5 °C margin
Orange	outside limits

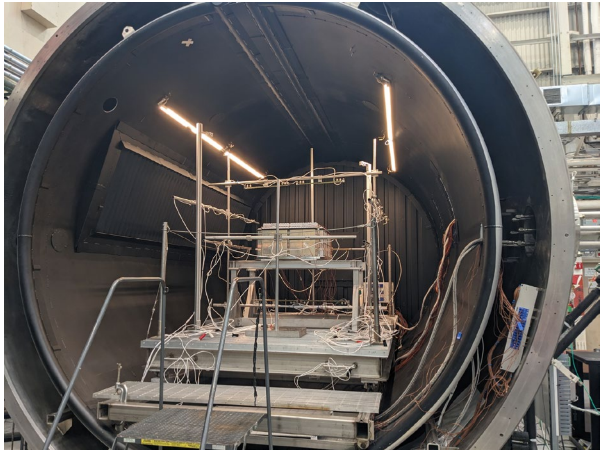
		Limits				Predictions					
		Op		Non-Op		WCH		WCC - Op		WCC - Non-Op	
	Component	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
	Baseplate*	40	-30	45	-30	23.68	15.42	-2.45	-8.28	-13.60	-18.15
CDU Temps [°C]	Crystals	30	-25	45	-30	22.27	18.62	-4.24	-6.13	-14.50	-16.32
	SiPM	30	-25	45	-30	22.17	19.29	-4.79	-4.84	-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	

T-Vac Set Up

- The StarBurst instrument was tested in Chamber V15 at MSFC.
  - 12 ft diameter
  - LN2 shroud for cooling
  - IR lamps in 6 zones (2 lamps each) for heating
  - Instrument sitting on PTFE standoffs atop two aluminum sawhorses
- Radiation sources were placed in the chamber to test instrument operation.
- 41 type T external thermocouples, attached with aluminum tape, were recorded throughout the entire test.
  - CDUs - 2 locations each
    - Center of each SiPM tray
    - Center of each window (facing out of instrument)
  - Baseplate - 4 locations at points of contact to sawhorse
  - Sawhorse - 4 locations at points of contact to baseplate
  - CDU support truss - 8 locations across interfaces
  - CEB lid
- Internal flight temperature sensors were recorded only when the instrument was powered on.
  - CDUs - 2 locations each
    - Internal sensor on each SiPM
    - Center of each enclosure (facing into instrument)
  - Baseplate - 3 locations
  - CEB
    - HexMorphos - 2 locations each
    - Xiphos Q8S - 3 locations
    - Power Board - 4 locations
    - IO Board



StarBurst Instrument after TC Attachment.



StarBurst Instrument in V15.

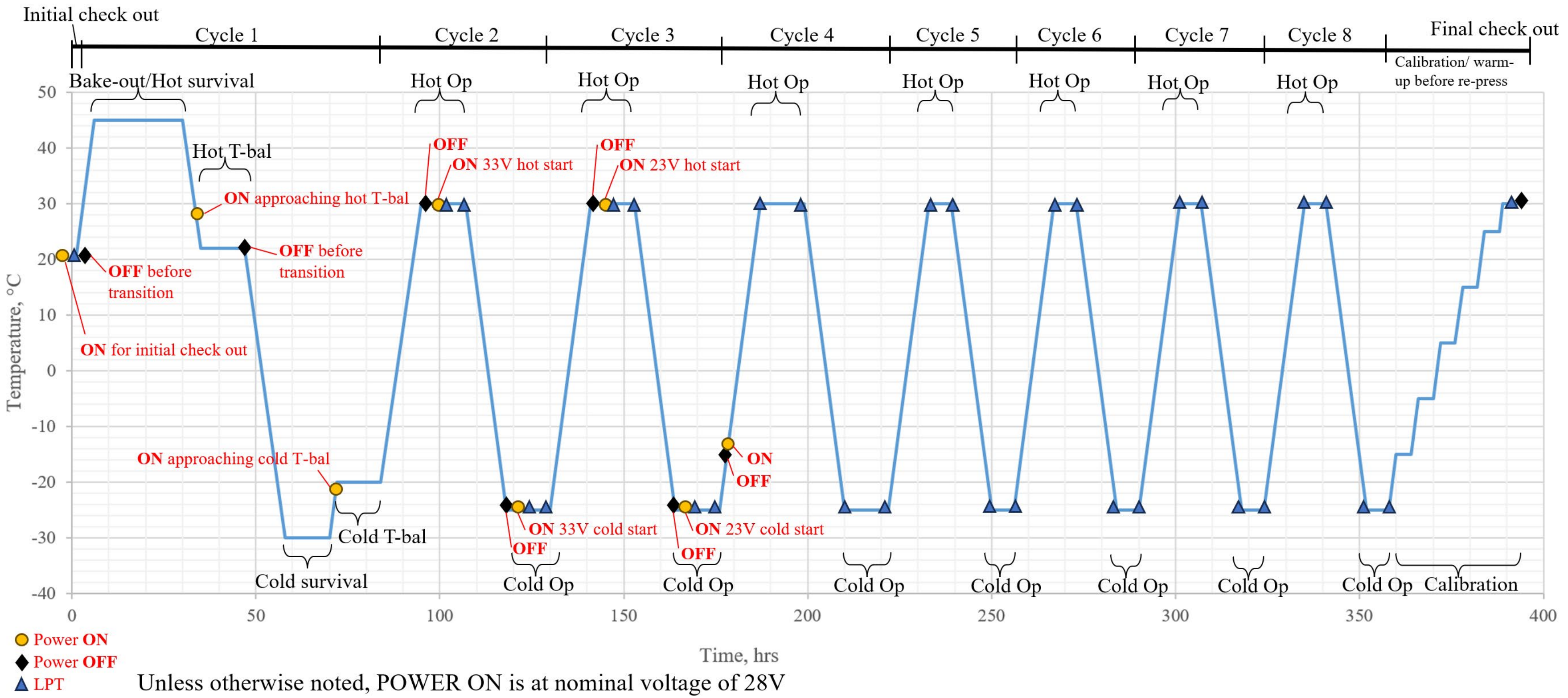
T-Vac Profile

- GEVS recommendations for protoflight instrument level t-vac were referenced.
  - Number of cycles: 4
  - Length of dwells: 12 hrs
  - Plateau temperatures: Max predicted temperatures +/-10 °C
- Recommendations were tailored to StarBurst.
  - Number of cycles: Increased to 8
    - 4 cycles with 12+ hr dwells
      - 1st cycle hot dwell: 24 hr bakeout/survival plateau
      - Hot thermal balance
      - 1st cycle cold dwell: 12 hr survival plateau
      - Cold thermal balance
      - 2nd - 4th cycles: 12 hr operational dwells
    - 4 ‘risk reduction cycles’ with 6+ hr dwells
  - Risk reduction cycles were added because no t-vac cycles were performed at the component level and only 1 cycle was planned for the spacecraft level.
  - Two hot and cold starts to test voltage corners
  - Margin selected to not exceed CDU hot operation limits
    - Hot margin ~8 °C
    - Cold margin >10 °C
  - Calibration steps at 10 °C increments during transition from last cold dwell to ambient temperature to calibrate the instrument

Planned T-Vac Parameters

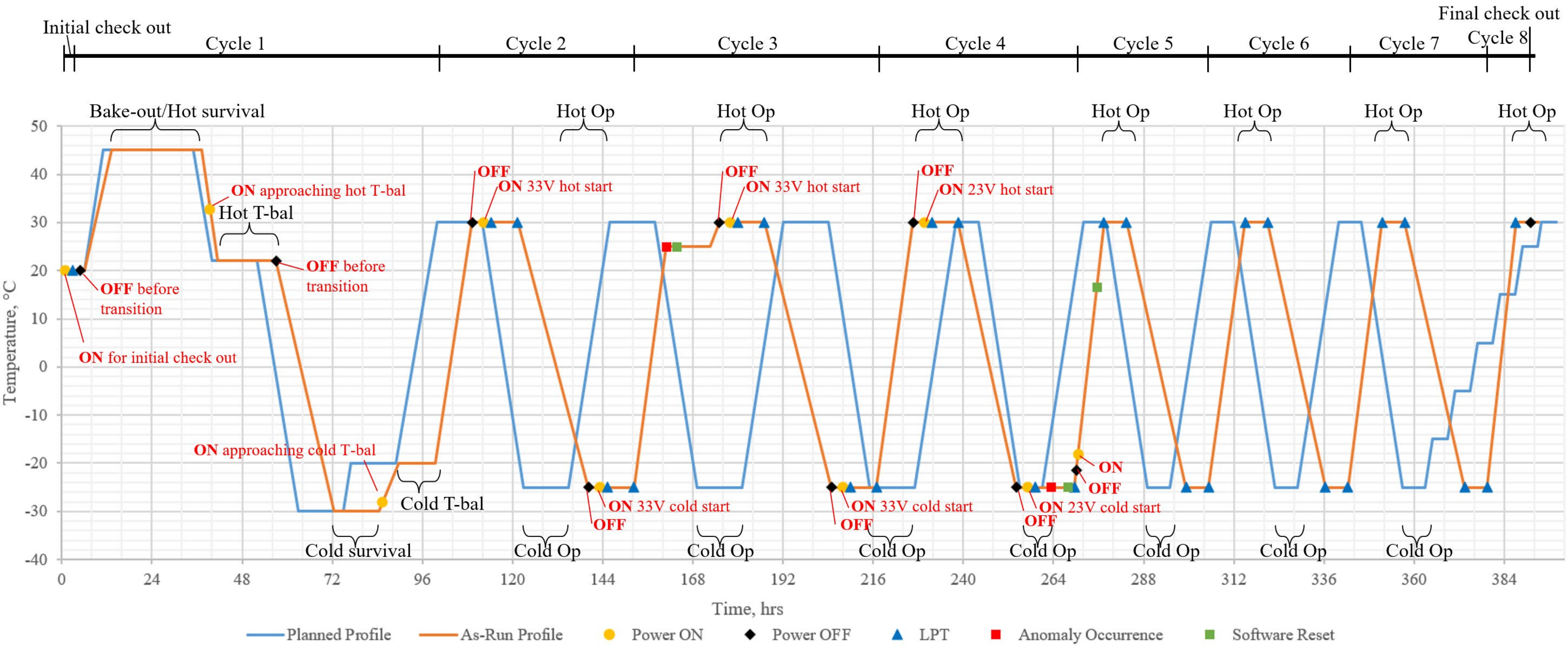
- Survival Limits Plateaus
  - Hot survival / bakeout: +45 °C +0/-2 °C
  - Cold survival: -30 °C +2/-0 °C
  - Instrument power: off
  - Control temperatures: External CDU sensors
- Thermal Balance Plateaus
  - Hot thermal balance: +22 °C ± 2 °C
  - Cold thermal balance: -20 ± 2 °C
  - Instrument power: on
  - Control temperatures: all TCs
  - Steady state: goal < 0.01 °C/hr
- Operational Limits Plateaus
  - Hot operational plateau: +30 °C +0/-2 °C
  - Cold operational plateau: -25 °C +2/-0 °C
  - Instrument power: on
  - Control temperatures: Internal CDU sensors

Planned T-Vac Profile



Unless otherwise noted, POWER ON is at nominal voltage of 28V

As-Run T-Vac Profile



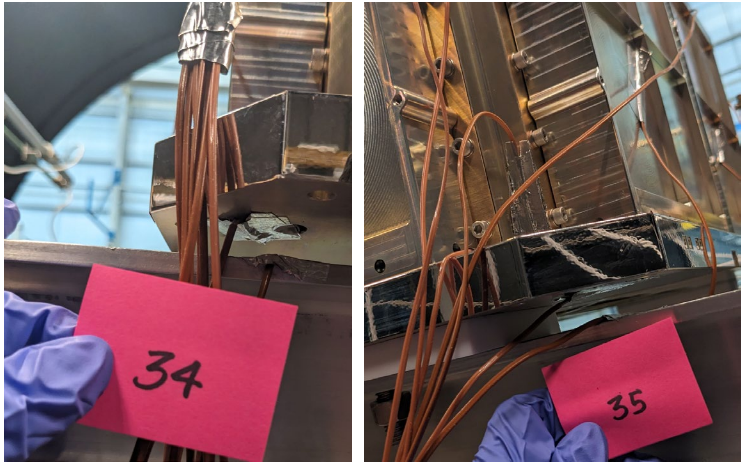
Unless otherwise noted, POWER ON is at nominal voltage of 28V

Why the Differences?

- The transitions between hot and cold plateaus took additional time. The team was initially conservative with lamp adjustments to not exceed 10 °C/hr rate of change limit.
- The limit of the hot plateau was increased to 30 °C +/-2 °C upon realization of updated CDU temperature limits.
- Hot thermal balance required additional time due to unplanned environment changes.
  - Instrument restarts
  - Test locations external environment changes
- Q8S anomalous behavior was observed in which the processor spontaneously restarted.
  - The test was paused at the first occurrence to obtain project management guidance on how to proceed.
  - The test plan was adjusted to accommodate troubleshooting.
- Calibration steps were removed because data was collected during transition periods. It was determined steady holds at each calibration temperature was not required.
- Cycles by ½ (did not perform final cold plateau) due to schedule restraints.

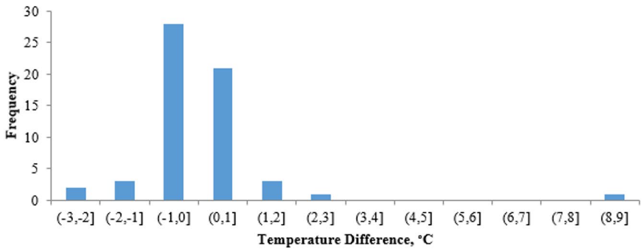
Test Data for Model Correlation

- Hot and cold thermal balance holds both achieved steady state <0.1 °C/hr.
- 60 and 59 temp sensors on the StarBurst Instrument were used for correlation for cold and hot cases, respectively.
  - External thermocouples: 37 (and 36) thermocouples referenced
  - Internal flight temperature sensors: 23 sensors referenced
    - CDUs - only internal SiPM Board sensor referenced
    - HexMorphos - 2 locations each
    - Xiphos Q8S - 3 locations
    - Power Board - 4 locations
    - IO Board
- All correlated model temperatures are within 3 °C of test temperatures, besides one.
  - One outlier (TC34) is on baseplate corner. Assumed that TC tape partially lifted.
    - Out-of-family with other baseplate temperatures in proximity.
    - Test data is colder than model data => closer to t-vac environment

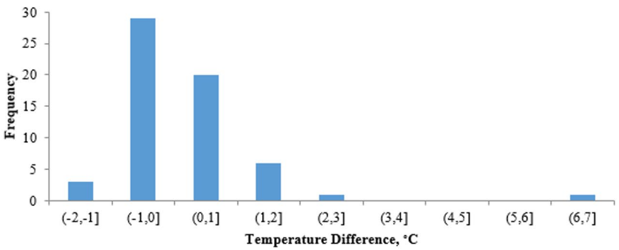


TC34 and TC35 are both in difficult to reach locations beneath the baseplate and above the sawhorse. TC35 tape is much more smoothed down.

Hot Thermal Balance Histogram



Cold Thermal Balance Histogram



Model Updates

- A test model was built to use for correlation to test data by removing and adding the appropriate components.
  - Removed: spacecraft, MLI, radiator, orbital environments
  - Added: chamber, sawhorse boundary nodes, measure points representing test sensor locations for temperature comparison
- Updates were made to the test model to decrease the difference between model temperature predictions and test data.
  - Boundary temperatures were adjusted to match external hardware model temperatures to test temperatures. Chamber hardware and test support equipment was not modeled as explicit geometry.
  - Heat dissipations were updated to match the measured power input values during test.
  - Power board
    - EMI filter and DC converter locations updated
    - Added fidelity by adding components instead of smearing power across board
    - Contacts between chips/boards and board/enclosure
  - HexMorphos
    - Added fidelity and modeled highest heat dissipating chip to show localized heating
    - Reduced thermal contact between hexMorphos and mounting plane
    - Reduced wedgelock contacts
  - CEB enclosure
    - Updated optical properties of internal surfaces

Post-Model Correlation Results

- Differences from pre-t-vac flight predictions:
  - Crystal and SiPM temperatures decreased in both WCH and WCC.
    - Due to less heat radiated from CEB enclosure to CDUs.
  - Power board, DC converter, and EMI filter temperature decreased.
    - Due to modeling additional components on power board with their individual heat dissipations.
  - SlimMorphhos and hexMorphos temperatures increase.
    - Due to modeling localized heating on hexMorphos and reducing thermal contact from hexMorphos to mounting planes and Wedgelocks contact .

Green	> 10 °C margin
Yellow	5 to 10 °C margin
Light orange	0 to 5 °C margin
Orange	outside limits

		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	

Additional Testing

- The StarBurst instrument was delivered to SFL and integrated with the spacecraft.
- The spacecraft level t-vac includes thermal balance, day-in-the-life testing, and 1 cycle.
- Results from the spacecraft level t-vac will further inform the instrument thermal model by providing data to verify aspects not present in the instrument level t-vac test.
  – MLI performance and contact
  – Heat transfer between instrument and bus
  – Radiator contact and performance
  – Heater operation

Lessons Learned

- Requirements/limits
  - Press for “real” temperature limits.
  - Ask what temperatures/environments hardware (or similar hardware) has previously been tested to.
  - Numbers in requirements are not necessarily hardware limits.
  - Ask rationale behind thermal requirements.
- Hardware assembly and assumptions vs. reality
  - Check templates on actual hardware.
  - GE Handbook method for calculating contacts proved accurate.
  - Wedgelock contacts may not be as perfect as calculated based on datasheet information.
- Team planning and preparation
  - Ensure there is consistent labeling of components between teams.
  - Ensure full test team is aware of operation needs to gather needed data.
  - Change as little as possible in environment outside of t-vac chamber.
  - Prepare guidelines for off nominal situations.

Summary

- The thermal analysis and design of the StarBurst Instrument was performed at MSFC using Thermal Desktop software.
- Protoflight thermal vacuum testing was performed on the assembled flight instrument and included bakeout, hot survival, cold survival, hot thermal balance, and cold thermal balance, in a total of 7.5 cycles.
- Data from the thermal vacuum testing was used to correlated a thermal model within 3 °C of test data.
- Updates were made to the Starburst Instrument flight model to produce higher accuracy flight temperature estimates.
- Further thermal vacuum testing will be performed after integration at the Spacecraft level.
- Launch in 2027!

Acknowledgements

- Thank you to StarBurst team and test team support in contributing to a successful thermal vacuum test!

Questions?

Thank you for your time!