TFAWS Short Course

Thermal Testing

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Agenda

- Introduction
- Background/History
- Thermal Testing Overview
- Requirements
- Test Setup
- Thermal Analysis and Documentation

1.0 Introduction & Overview

- "Thermal testing" is a broad topic that would be impossible to cover in a short course format. There are so many unique situations and specialties that a week of short courses could easily be filled.

- This short course presents the basics of satellite thermal testing, with a slant to the Goddard philosophy. Hopefully will generate interest for more detailed discussions/topics and even similar courses on other specialties at future TFAWS.

- Please ask questions where you think appropriate, and I will answer or defer to a later point in the course, or sidebar.

- Please provide comments or suggestions on how to improve this course – likely it will be used again.

Why Do We Need Thermal Testing ?

History/Background

- To understand how today's requirements came to be, some historical perspective is needed.
- Environmental testing has it's roots in World War II with the development of electronic systems. As technology improved, and products downsized, complexity increased. Compliance to design requirements no longer equated to reliability over an extended lifetime.
- Burn-in testing – powering electronics at high temperatures for extended time periods– was introduced in the 1960's to precipitate these early failures.
- The military introduced standards requiring testing in simulated environmental extremes. Thermal cycling (along with vibration testing) became the basis for Environmental Stress Screening (ESS).

NASA History/Background

- NASA Goddard Space Flight Center was established in May 1959 (previously the Beltsville Space Center) and has since had a long history of developing space flight hardware and environmental testing of that hardware.
- But, before NASA, there was aeronautical and aerospace work:
  - 1915 National Advisory Committee for Aeronautics (NACA)
  - 1936 Guggenheim Aeronautical Laboratory at the California Institute of Technology (GALCIT)
- Unfortunately, info on very early thermal testing is difficult to find.

Early Testing at GSFC

- NASA TN D-1748 “EXPERIENCE IN THERMAL-VACUUM TESTING EARTH SATELLITES AT GODDARD SPACE FLIGHT CENTER” (A. Timmins, K. Rosette), August 1963
  - Summarized testing of first 3 spacecraft
    - Explorer X 1 prototype, 3 flight
    - Explorer XII 1 prototype, 2 flight
    - Ariel I 1 prototype, 2 flight

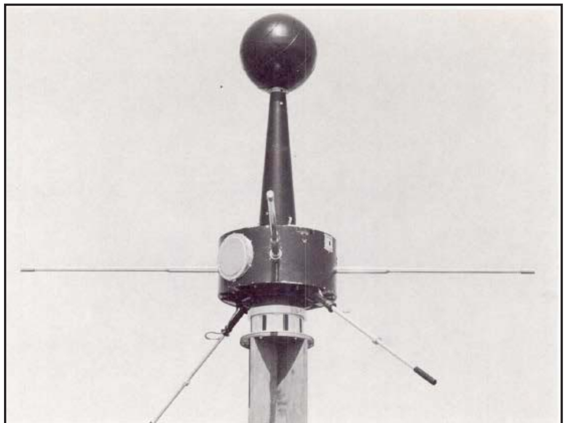


Figure 2—Explorer X, the Interplanetary Probe.

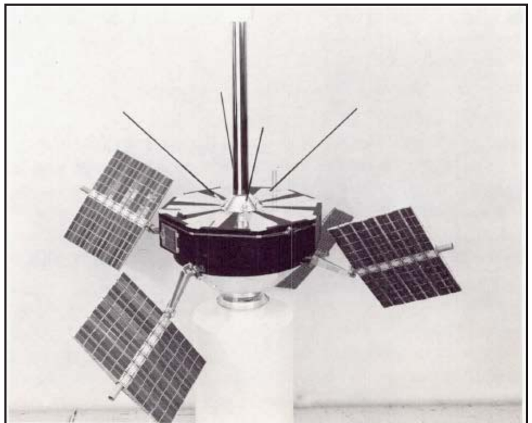


Figure 3—Explorer XII, the Energetic Particles Satellite.

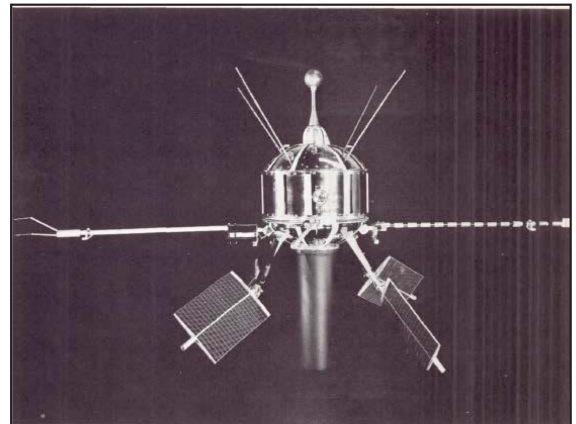


Figure 4—Ariel I, the International Ionosphere Satellite.

Scheduled Test Times (days).

Spacecraft	Hot	Cold	Gradient	Total
Explorer X				
Prototype	1.25*	1.25*	--	2.5
Flight Units	1	1	--	2
Explorer XII				
Prototype	2	2	4	8
Flight Units	--	1	4	5
Ariel I				
Prototype	3	2	2	7
Flight Units	3	2	--	5

*Half of battery life.

- While it isn’t clearly documented, it seems that thermal vac testing back then was only a few days with multi-day hot and cold soaks, and a “thermal gradient” test, that evolved into several cycles.

Early Test Results

Summary of Failures in Thermal-Vacuum Tests.

Spacecraft	Type of Test: Hot		Type of Test: Cold		Totals*
Prototype:					
Explorer X	4	24	0	15	39
Explorer XII	6		4		
Ariel I	14		11		
Flight Units:					
Explorer X	2	5	6	28	33
Explorer XII	0		11		
Ariel I	3		11		
Totals*		29		43	72

*Totals do not include setup, corona, or operator failures.

Table 3

Summary of Types of Failures.*

Type System	Test	Mechanical†	Component	Design‡	Thermal**	Totals
Prototype	Cold	2	7	3	3	15
	Hot	6	9	2	7	24
Flight	Cold	4	10	9	5	28
	Hot	0	1	2	2	5
Totals	Cold	6	17	12	8	43
	Hot	6	10	4	9	29
Grand Total		12	27	16	17	72

*Does not include setup, corona, or operator failures.
†Mechanical failures include cold solder joints, connectors, sheared screws, and broken leads.
‡Design failures include underrated components and unbalanced circuits.
**Thermal failures include inadequate heat sinks, poor thermal contacts, and temperature sensitivity.

How Well Did That Testing Work ?

- Explorer X (Interplanetary Probe) launched on March 25, 1961. Its transmitters functioned for the expected life of the spacecraft (60 hours). One failure was encountered. Temperature measurements inside the sphere housing the rubidium vapor magnetometer showed a continuous rise for several hours after satellite injection. When the temperature rose above 55° C after 2 hours, the rubidium vapor magnetometer operation became intermittent. Postflight tests demonstrated that, during launch, out-gassing of the hot nose cone surface adjacent to the sphere caused deposition of a film on the sphere that greatly increased the absorptivity of the surface. This caused the temperature to be higher than predicted.
- Explorer XII (Energetic Particles Satellite) was launched from Cape Canaveral on August 15, 1961. Operation of the satellite ceased abruptly at 1: 12 EST on December 6, 1961, after 112 days of operation. All experiments functioned perfectly during its orbital life. The exact cause of the failure has not been determined.
- Ariel I (International Ionosphere Satellite) was launched from Cape Canaveral on April 26, 1962. The Lyman-alpha experiment failed on launch. Otherwise, operation of the spacecraft was perfect until July 12, 1962, at which time the system began to go into IS-hour periods of undervoltage. As of December 1962, Ariel I had a total equivalent operating time of 127 days. The spacecraft was continuing to send good scientific data approximately one-third of the time. The intermittent operation was attributed to degradation of the solar array and other damage caused by the enhanced radiation belt that resulted from the high-altitude nuclear detonation which occurred on July 9, 1962.

Recommendations ?

- The laboratory and flight data presented were insufficient to form any firm test times. However, some useful estimates were made, such as:
  - Prototype spacecraft: (hot) 6 days (cold) 4 days
  - Flight unit spacecraft: (hot) 4 days (cold) 4 days
  - The ± 10°C margin used for prototype spacecraft testing should be continued.

- Update in 1966 (NASA TN D-3713):
  - Seven of the 10 operated for the full planned lifetime of the satellite, and the other three had lifetimes of 112, 193, and 312 days.
  - Recommend minimum of six days at each thermal extreme
  - simulation of high rate of change of temperatures as well as simulation of large thermal gradients when applicable.

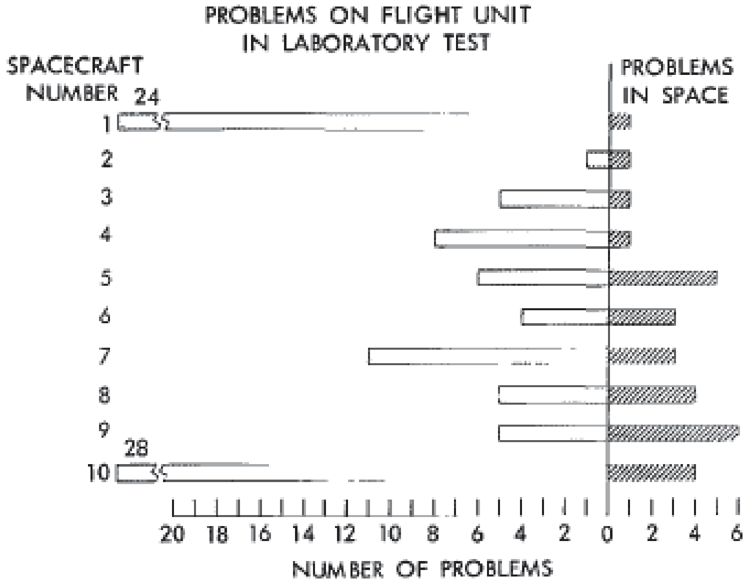


Figure 11—Comparison of space problems with test problems for ten spacecraft.

More Updates

- Current (and future) test philosophy is (will be) based on success record.
- Study done in 1970 summarized the total space life performance of 57 Goddard Space Flight Center spacecraft. This was done to justify a continuation of the Goddard philosophy requiring a system level environmental test.
  - Four meteorological spacecraft
  - Two astronomical observatories
  - Six geophysical observatories
  - Six solar observatories
  - Six applications technology spacecraft
  - Seven interplanetary monitoring platforms
  - Twelve operational weather spacecraft
  - Fourteen miscellaneous scientific missions
- The time distribution of 449 malfunctions, of which 248 were classified as failures, is presented. Test data were available for 39 of the spacecraft and permitted a comparison of system test performance with the first day, first-month, and total space life performance.

GSFC Philosophy – leads to GEVS predecessors

Evolution of GEVS

- Throughout most of the 1960's, test requirements were created for each launch vehicle and provided specific tests and test levels.
  - 1962 General Environmental Test Specification for Delta Launched Spacecraft, Goddard Space Flight Center, Preliminary Draft,.
- In 1969 the first general environmental test specification was published covering several expendable launch vehicles (ELV's).
- It is important to understand how GEVS has developed over the years. These methods have resulted in a record of mission success.
- Historical GEVS-type documents at GSFC
  - 1969 S-320-G-1 General Environmental Test Specification for Spacecraft and Components
  - ??? GETS General Environmental Test Specification for ELV Payloads
    - last revision in 1978
  - 1984 GEVS General Environmental Verification Specification for STS Payloads, Subsystems and Components
  - 1990 GEVS-SE General Environmental Verification Specification for STS & ELV Payloads, Subsystems and Components
    - Rev A 1996
  - 2005 GSFC-STD-7000 GENERAL ENVIRONMENTAL VERIFICATION STANDARD (GEVS) For GSFC Flight Programs and Projects
    - Rev A 2013

GEVS

- GEVS: General Environmental Verification Specification for NASA Goddard Space Flight Center. It provides requirements and guidelines for environmental verification programs for GSFC missions, at the payload, subsystem and component (units) level.
  - The Systems Management Office (SMO) which is part of the Goddard Office of Systems Safety and Mission Assurance (OSSMA) is responsible for setting verification policy and publishing the GEVS. The requirements are constantly under evaluation and recommendations for changes being gathered. The revision process is worked very closely with the Applied Engineering and Technology Directorate (AETD).

More Later

How do you generate test requirements?

- What is/are the expected failure mechanisms?
- Develop a test philosophy to exploit those weaknesses.
- Failures typically fall into 4 categories:
  - Early failures caused by a major design weakness.
  - Early failures resulting from defects in material or workmanship.
  - Random failures whose frequency of occurrence is a function of design and quality control.
  - Wear-out failures.
- The systems test program is directed chiefly at eliminating those failures which arise from the first two causes.
  - Prototype testing is directed at qualifying the design and eliminating failures due to the first category.
  - Testing of the [proto]flight unit is intended then to discover failures in the second category.

2.0 Thermal Testing Overview

- Types of thermal testing, includes qualification, engineering development, life test, and verification testing. We'll be focusing on verification testing.

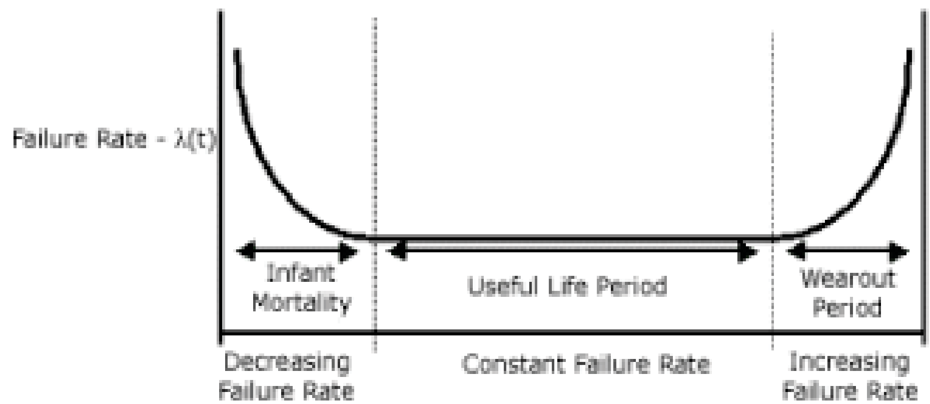
- Thermal verification testing is one of several environmental screening tests done in support of flight projects .
  - At the instrument and spacecraft level, thermal testing is the most complex and costly of the environmental tests, and can last for weeks or months.

- Thermal Balance:
  - Verification of the thermal design in simulated mission bounding environments/conditions
  - Provide data for model correlation to give confidence in final mission predictions
  - Demonstrate performance over range of simulated mission temperatures in different modes.

- Thermal Cycles:
  - Environmental Stress Screening (ESS) of test article
  - Demonstrate the performance of the test item in vacuum at a temperature range outside those allowed for the mission.

What is Environmental Stress Screening (ESS) ?

- Statistically anything as complex as a spacecraft can NOT be 100% defect free.
- Sometimes these defects are found through post-manufacturing inspections, but latent defects cannot be detected thru inspections and get past that point only to fail later.
- Makes sense to test early, at lower levels, to mitigate risk.



- ESS is "…the application of accelerated environmental stimuli, within design capability, to powered electronics in order to precipitate latent part and workmanship defects to observable failures….."
- The goal of ESS is to uncover these latent (hidden) defects before flight, i.e.- find them during the left side of the bathtub curve, without substantially reducing the life of the unit.
- How to do this most effectively………and without an unlimited budget…..and minimize schedule impact/risk……

Types of Failures/Issues

- Parts defects: bulging packages, case rupture,
- PCB defects: delam, trace lift, card guide under-torque
- Solder issues: poor fillets, coverage
- Bond separations: for “high” power parts to boards
- Tolerance stack-up issues: CTE effects could cause shorting
- Thermal mismatches:
- Changes in electrical characteristics: FPGAs, timing,

Level of Assembly

- **Spacecraft:** Observatory (SC Bus + Science Instruments), LV Payload,
- Module: Spacecraft Bus, Science Payload, Payload Fairing
- **Subsystem:** Instrument/Experiment, Structure, Attitude Control, C&DH, Thermal Control, Electrical Power, TT&C, Propulsion
- Section: Electronic Tray or Pallet, Stacked units, Electronic Boxes Mounted on a Panel, Solar Array Sections
- **Unit:** Electronic Box, Gyro Package, Motor, Actuator, Battery, Receiver, Transmitter, Antenna, Solar Panel, Valve Regulator
- Assembly: Power Amplifier, Regulator
- Subassembly: Wire harness, Loaded PCB
- Part: Resistor, Capacitor, IC, Switch, Connector, Bolt, Screw, Gasket, Bracket, Valve Stem

Robust testing at lower levels of assembly mitigates issues at higher levels when schedule impact of anomalies is more severe

Units

- Without trying to provide an absolute definition of what a "unit", I think of a "unit" typically as the "smallest thing you bolt on" at SC assembly. Most commonly:
  - Electronic boxes of all types
  - Propulsion valves, thrusters, pressure transducers,
  - Batteries
  - RWAs
  - RF stuff (besides SSPAs, amps, etc)
  - Antennas (of all types)
  - Mechanisms: hinges, dampers, SADAs, gimbals,
  - Structural stuff
  - Solar arrays

Unit Level Thermal Testing

- Units typically are “procured” and can have a purely conductive or radiativel (or both) thermal design, with mounting I/F temperature range specified that they must operate and meet performance requirements within.
- Testing at the unit level is almost always only for stress screening and performance margin. Typically mount to a platen/coldplate inside a vacuum chamber that is controlled to the spec temperatures.
- “Survival” and “Safe” (or “Safehold”) are spacecraft operating modes. In these modes, units are either ON or OFF. Units have “Operational” and “Non-Operational” modes
  - The unit dissipations may be different due to usage: voltage converter efficiencies vs load, battery dissipation versus I_{BUS} or DOD, etc, COM in “quiescent/idle” vs “transmit, RWA rpm, etc
  - Non-Op is OFF – plain and simple……
- Objectives of Unit testing:
  - Environmental Stress Screening (ESS) thermal cycles; burn-in; survival/turn-on
    - Electronics: typically temperature controlled platen, with ambient or controlled radiative sink
    - Mechanisms: lamps, heaters, controlled radiative sink
  - Measure electronics power at temperature extremes
  - Bakeout

Subsystem/Instrument Level

- For GSFC missions, this is almost always instrument level test.

GOES-R SUVI

GOES-R ABI

- Some exceptions:
  - JWST: although instruments are tested separately, there are higher level tests that can be considered “subsystems”.
  - TERRA: High Gain Antenna Assembly
  - Despun platforms ?
  - Others ?

Instrument Level Thermal Testing

- Instruments are almost always “procured” separately from the SC, and have their own specs/contracts/etc. Most are thermally isolated, but still have I/F temperature requirements where they must operate and meet performance requirements at.
  - Sometimes there are separate electronics boxes with a conductive I/F; thermal testing of these will be like units.
- Instrument can be like unit, either ON or OFF, but usually they are more confusing.
- Objectives of Instrument testing:
  - Environmental Stress Screening (ESS) thermal cycles; burn-in; survival/turn-on
  - Thermal balance testing: Radiative zones w/temperature controlled I/F’s
    - Thermal control verification
    - Thermal model correlation
  - Measure electronics power at temperature extremes
  - Bakeout
-

Spacecraft Level Thermal Testing

- Also referred to as “System” level testing.
- Note that most likely there will be NO conductive I/Fs for the SC during the mission ! So the key to thermal testing is the radiative environments you need to determine and simulate.
- Spacecraft are never (?) OFF after launch; some minimal configuration is ON to provide basic power distribution and C&C function. This is usually “Survival” mode.
- Objectives of SC testing:
  - Final Environmental Stress Screening (ESS) thermal cycles; burn-in; survival/turn-on
  - Thermal balance testing: Radiative zones w/temperature controlled I/F’s
    - Thermal control verification
    - Thermal model correlation
  - Measure electronic power at temperature extremes
  - Final bakeout

Ambient Pressure Thermal Cycles

- Thermal vacuum testing is the preferred approach.
- Cost savings of cycling in ambient pressure lead to the obvious question “can we substitute ambient pressure cycles for the preferred vacuum cycles”?
- Issues include:
  - Temperature distribution differences due to additional convective heat transfer paths
    - Timing differences, T_{MAX} masked,
  - Vacuum sensitivity (corona, multipaction, fluid/lubricant leakage/migration, part deformation, etc)
- NASA Preferred Reliability Practice PT-TE-1409 “Thermal-Vacuum Versus Thermal Atmospheric Tests of Electronic Assemblies”.
  - “....if analysis shows that the ΔT effect is less than 5°C on all piece parts, solder joints, etc., and there are no known pure vacuum effects, then performing a T/A test in lieu of a T/V test might be allowed depending of the criticality of the unit under test. “

Ambient Pressure Thermal Cycles

- GSFC GEVS did allow for this (at the unit level), provided:
  - 50% additional cycles were completed
  - Operational temperature range extended by 15C at both ends.

- Some programs asked for convective analysis and would allow ambient testing if the "ΔT effect" was shown to b <5°C.
  - To my knowledge, this was only done once for a MAVEN unit that had heritage ambient, vacuum test, and flight data that showed this criteria was met.

- GSFC has removed this as an "option" in GEVS to force the waivers to completed with a full technical review before project approval can be obtained. This is intended for all units with dissipation, and/or vacuum sensitivity.

"The safest and simplest course of action is to T/V everything."

Thermal Balance Testing

- Typically done at subsystem/instrument and spacecraft levels.
  - Unit level thermal testing at plateaus is usually stable enough so that those models can be correlated.
  - Vendors usually have correlated models (if heritage). Otherwise, should insist on model and some level of model validation.
- The main objectives are to:
  - Verify the thermal design meets requirements. Demonstrate system requirements are met at over expected mission temperature range.
  - Verify the thermal model for mission predictions
  - Confirm thermal interfaces
- Minimum of 3 cases:
  - Operational mode at Hot and Cold mission environments
  - Non-operational mode at Cold Environment (sometimes Hot too)
  - Some missions may require more.

Thermal Vacuum Testing (Cycles)

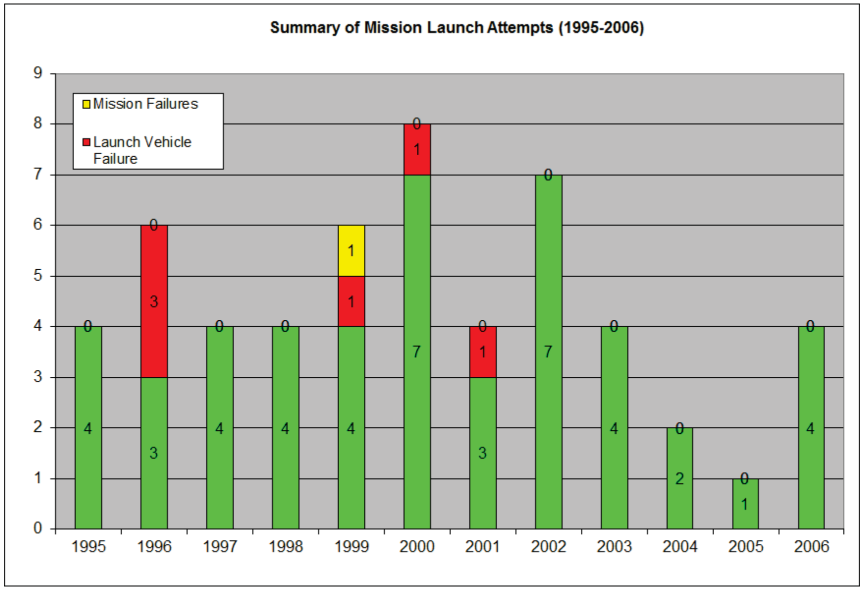
- Thermal vacuum cycling is one of the environmental tests done in support of flight projects. - usually performed last in the environmental test campaign (after mechanical) and has two purposes:
  - Demonstrate performance at temperatures outside (Qualification, Proto-flight, Acceptance) of the allowable operational limits
  - Environmental Stress Screening - thermal cycling is considered to be the single most stressful screening test of the environmental test campaign.
- GSFC practice is 12 cycles before flight –cycles at lower levels mitigates risk early in project - gives confidence that workmanship flaws are uncovered
  - Unit: 8
  - Instrument: 4 (and 4 at unit, or all 8 at instrument)
  - Spacecraft: 4

3.0 Requirements

- 3.1 General Environmental Verification Specification
- 3.2 GOLD Rules

GEVS

- GEVS applies to GSFC hardware and associated software that is to be launched on an ELV and applies to:
  - All space flight hardware, including interface hardware, that is developed as part of a payload managed by GSFC, whether developed by (1) GSFC or any of its contractors, (2) another NASA center, or (3) an independent agency; and
  - All space flight hardware, including interface hardware that is developed by GSFC or any of its contractors and that is provided to another NASA installation or independent agency as part of a payload that is not managed by GSFC.
- GSFC test verification has evolved over many years and many successful missions:
  - System performance
  - Electrical
  - Structural and Mechanical
  - Electro-Magnetic Compatibility
  - Thermal
  - Contamination Control
  - End-to-End Testing



What is the purpose of GEVS ?

- Describes methods for implementing those requirements and contains a baseline verification plan to demonstrate satisfactory performance of hardware in the expected mission environments, and that minimum workmanship standards have been met.
  - elaborates on those requirements,
  - gives guideline test levels,
  - provides guidance in the choice of test options, and
  - describes acceptable test and analytical methods for implementing the requirements.
- GEVS shall be used by GSFC projects and contractors.
  - tailor to create a project specific verification plan and verification specification.
  - GSFC projects must select from the options to fulfill the specific payload (spacecraft) requirements in accordance with the launch vehicle to be used, or to cover other mission-specific considerations.
- Most importantly – GEVS as a “ref doc” does NOT make it a requirement on a contractor……CUT & PASTE into your contractual documentation.

GEVS is not the Bible; rather it is a ***General* guideline to be used to develop a project thermal (and mechanical, etc) environmental verification plan.**

GEVS Overview

- 2.1 System
- 2.2 Environmental
- 2.3 Electrical
- 2.4 Structural & Mechanical
- 2.5 EMC
- 2.6 Thermal
  - 2.6.1 Summary
  - 2.6.2 Thermal Vacuum Qualification
  - 2.6.3 Thermal Balance Qualification
  - 2.6.4 Temperature-Humidity Verification
  - 2.6.5 Leakage (Integrity Verification)
- 2.7 Contamination Control

2.6.2 Thermal Vacuum Qualification:

Applicability
Special Considerations
Level of Testing
Test Parameters
Test Set-Up
Demonstration
Special Tests
Failure-Free Performance

2.6.3 Thermal Balance Qualification:

Alternative Methods
Use of a Thermal Analytical Model
Method of Thermal Simulation
Internal Power
Special Considerations
Demonstration
Acceptance Requirements

2.6.4 Temperature-Humidity Verification:

Temperature-Humidity Verification: Manned Spaces
Temperature-Humidity Verification: Descent and Landing
Temperature-Humidity: Transportation and Storage

2.6.5 Leakage (Integrity Verification):

Levels of Assembly
Demonstration
Acceptance Requirements

2.6.1 Summary of Requirements

- It is recommended that mechanical testing occur before thermal testing at the systems level.

- Electronic card/piece part thermal analyses shall be performed to ensure that the GSFC Preferred Parts List (PPL) derated temperature limits and the allowable junction temperatures are not exceeded during qualification test conditions.
  - Usually this is done at the box, or “unit” level.

2.6.2 Thermal Vacuum Qualification

2.6.2.1 Applicability

- All fight h/w shall be thermal vacuum tested
- GSFC utilizes a protoflight qualification test program

2.6.2.2 Special Considerations

- Unrealistic Failure Modes
- Avoiding Contamination
- Card Level Analysis Verification
- Test Temperature Sensor Location

Don't overstress.
Chamber bakeout/certification

Verify unit level analysis.

2.6.2.3 Level of Testing:

Unit, subsystem/instrument, payload/spacecraft/system

GR 4.27

2.6.2.4 Test Parameters

- Workmanship Margins
- Temperature Cycling
- Duration
- Pressure

Passive:	10C beyond AFT range
Active (cmd):	5Cbeyond setpoint range
Active (fix):	30% add'l
Cryo:	project specific

GR 4.29

Unit: 4 or 8, sub/Instr: min 4, SC: 4

Unit: 4hrs, sub/Instr: 12 hrs, SC: 24

< 1 X 10-5 torr

2.6.2 Thermal Vacuum Qualification (continued)

2.6.2.5 Test Set-Up

2.6.2.6 Demonstration

- Electrical Discharge Check → Launch config during chamber pumpdown
- Outgassing Phase → Bakeout
- Hot Conditions → Hot Turn-on
- Transitions → Remain operational, unless going to Cold Turn-on
- Cold Conditions → Cold Turn-on
- Hot and Cold Start Demonstrations
- Functional Tests → Plateaus shall be of sufficient duration to complete functional tests (FT at each plateau, except CPT at 1 hot and 1 cold)
- Return to Ambient
- General → Unique cases: meet with TEB/AETD

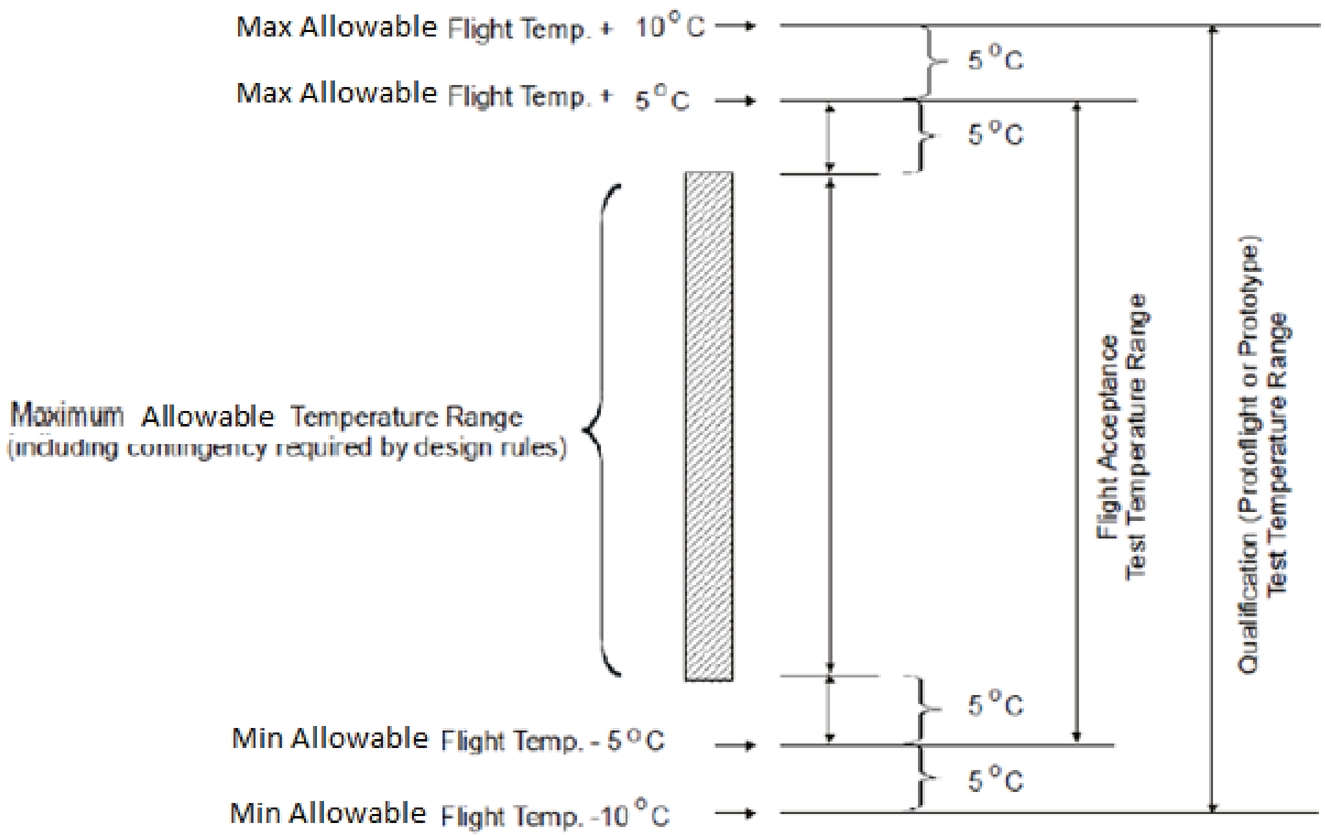
2.6.2.7 Special Tests

2.6.2.8 Failure-Free Performance

→ > 100 trouble-free hours functional operations at hot and at cold conditions
Total 350 hours failure-free hours is a requirement; 200 are to be in vacuum

Thermal Margins – GEVS Figure 2.6-2

GR 4.27



2.6.3 Thermal Balance Qualification

- **The thermal control system shall be verified under simulated on-orbit environments:**
  Hot & Cold Operational; Cold Safehold/Survival
- **Verify and correlate the thermal model.**
- **Thermal design margins shall be verified**

2.6.3.1 Alternative Methods
2.6.3.2 Use of a Thermal Analytical Model
2.6.3.3 Method of Thermal Simulation
- Solar input
- Planetary Input
- Interfaces
- Radiative Sink Temperatures
- Cryogenic Payloads
- Dewar Systems
- Coolers
- Zero-Q
- Avoiding Contamination
- Hardware Orientation

2.6.3.4 Internal Power
2.6.3.5 Special Considerations
2.6.3.6 Demonstration
2.6.3.7 Acceptance Requirements

Margins:
- Op Heater Max Duty Cycle — GR 4.25
- Survival Heater Margin
- I/F Heat Flow
- Selectable setpoints for 2Φ systems
- Heat transport for 2Φ systems
- Radiator rerjection — GR 4.25

Solar Sim
Cryopanels / Hater plates

Skin heaters
Cryopanels / Heater Plates
Quartz Lamps
Calrods

LN2: ~80-90 K
GN2: ~170-375 K
Lhe: ~20-30 K

Measure within 1%

Pressure < 1 X 10-5 torr

Stabilization Criteria
Correlation Error

GOLD Rules
(Goddard Open Learning Design)

GOLD Rules (It is NOT the GOLDEN Rules.......)

- GSFC-STD-1000e "Rules for the Design, Development, Verification, and Operation of Flight Systems"
- Further emphasizes some GEVS rules that every GSFC project must conform to.
- Sound engineering principles and practices, which have evolved in the Goddard community over its long and successful flight history.
- Intended to describe foundational principles that "work," without being overly prescriptive of an implementation "philosophy.
- Establish the methodology necessary to consistently and efficiently achieve safety and mission success for all space flight products
- Ensure that GSFC Senior Management will not be surprised by late notification of noncompliance to sound and proven engineering principles
- Intended to apply to all space flight products, regardless of implementation approach or mission classification
- A technical authority designated for each rule will be responsible for:
  - validating the principle, rationale, verification requirements, related guidance and lessons learned,
  - participating in the evaluation of proposed changes and waivers.

GOLD Rules

1.0 Systems Engineering
- 1.01 Reserved
- 1.02 Reserved
- 1.03 Reserved
- 1.04 Reserved
- 1.05 Single Point Failures
- 1.06 Resource Margins
- 1.07 End-to-End GN&C Phasing
- 1.08 End-To-End Testing
- 1.09 Test As You Fly
- 1.10 Reserved
- 1.11 Qualification of Heritage Flight Hardware
- 1.12 Reserved
- 1.13 Reserved
- 1.14 Mission Critical Telemetry and Command Capability
- 1.15 Reserved
- 1.16 Reserved
- 1.17 Safe Hold Mode
- 1.18 Reserved
- 1.19 Initial Thruster Firing Limitations
- 1.20 Manifold Joints of Hazardous Propellants
- 1.21 Over-pressurization Protection
- 1.22 Purging of Residual Test Fluids
- 1.23 Spacecraft 'OFF' Command
- 1.24 Propulsion System Safety Electrical Disconnect
- 1.25 Redundant Systems
- 1.26 Safety Inhibits & Fault Tolerance
- 1.27 Propulsion System Overtemp Fuse
- 1.28 Unintended Propellant Vapor Ignition
- 1.29 Reserved
- 1.30 Controller Stability Margins
- 1.31 Actuator Sizing Margins
- 1.32 Thruster and Venting Impingement
- 1.33 Polarity Checks of Critical Components
- 1.34 Closeout Photo Documentation of Key Assemblies
- 1.35 Maturity of New Technologies
- 1.36 Reserved
- 1.37 Stowage Configuration
- 1.38 Reserved

2.0 Electrical
- 2.01 Flight Electronic Hardware Operating Time
- 2.02 EEE Parts Program for Flight Missions
- 2.03 Radiation Hardness Assurance Program
- 2.04 Reserved
- 2.05 System Grounding Architecture
- 2.06 System Fusing Architecture
- 2.07 End-to-End Test of Release Mechanism for Flight Deployables
- 2.08 Reserved
- 2.09 Reserved
- 2.10 Reserved
- 2.11 Reserved
- 2.12 Printed Circuit Board Coupon Analysis

3.0 Software

3.01 Verification and Validation Program for Mission Software Systems
3.02 Elimination of Unnecessary and Unreachable Software
3.03 High Fidelity Interface Simulation Capabilities
3.04 Independent Software Testing
3.05 Flight / Ground System Test Capabilities
3.06 Dedicated Engineering Test Unit (ETU) for Flight Software (FSW) Testing
3.07 Flight Software Margins
3.08 Reserved
3.09 Reserved
3.10 Flight Operations Preparations and Team Development
3.11 Long Duration and Failure Free System Level Test of Flight and Ground System Software
3.12 Reserved
3.13 Maintenance of Mission Critical Components
3.14 Command Procedure Changes
3.15 Reserved

GOLD Rules

4.0 Mechanical

- 4.01 Reserved
- 4.02 Reserved
- 4.03 Factors of Safety for Structural Analysis and Design, and Mechanical Test Factors & Durations
- 4.04 Reserved
- 4.05 Reserved
- **4.06 Validation of Thermal Coatings Properties**
- 4.07 Solder Joint Intermetallics Mitigation
- 4.08 Space Environment Effects on Material Selection
- 4.09 Reserved
- 4.10 Minimum Workmanship
- 4.11 Testing in Flight Configuration
- 4.12 Structural Proof Testing
- 4.13 Reserved
- 4.14 Structural and Mechanical Test Verification
- 4.15 Torque Margin
- 4.16 Reserved
- 4.17 Reserved
- 4.18 Deployment and Articulation Verification
- 4.19 Reserved
- 4.20 Fastener Locking
- 4.21 Brush-type Motor Use Avoidance
- 4.22 Precision Component Assembly
- 4.23 Life Test
- 4.24 Mechanical Clearance Verification
- **4.25 Thermal Design Margins**
- 4.26 Reserved
- **4.27 Test Temperature Margins**
- **4.28 Thermal Design Verification**
- **4.29 Thermal-Vacuum Cycling**

- 5.0 Instruments
- 5.01 Reserved
- 5.02 Reserved
- 5.03 Reserved
- 5.04 Instrument Testing for Multipaction
- 5.05 Fluid Systems GSE
- 5.06 Flight Instrument Characterization Standard
- 5.07 Reserved
- 5.08 Laser Development Contamination Control
- 5.09 Cryogenic Pressure Relief

GOLD Rule 4.25 - Thermal Design Margins

4.25	Thermal Design Margins				Mechanical		
Rule: R	Thermal design shall provide adequate margin between stacked worst-case flight predictions and component allowable flight temperature limits per GEVS 2.6 and 545-PG-8700.2.1A. Note: This applies to normal operations and planned contingency modes. This does not apply to cryogenic systems.						
Rationale:	Positive temperature margins are required to account for uncertainties in power dissipations, environments, and thermal system parameters.						
Phase:	<A	A	B	C	D	E	F
Activities:	1. Thermal design concept produces minimum 5C margins, except for heater controlled elements which have a maximum 70% heater duty cycle, and two-phase flow systems which have a minimum 30% heat transport margin. For Pre-A, larger margins advisable.	1. Thermal design concept produces minimum 5C margins, except for heater controlled elements which have a maximum 70% heater duty cycle, and two-phase flow systems which have a minimum 30% heat transport margin. For Phase A, larger margins advisable.	1. Thermal design concept produces minimum 5C margins, except for heater controlled elements which have a maximum 70% heater duty cycle, and two-phase flow systems which have a minimum 30% heat transport margin.	1. Thermal design concept produces minimum 5C margins, except for heater controlled elements which have a maximum 70% heater duty cycle, and two-phase flow systems which have a minimum 30% heat transport margin.	1. System thermal balance test produces test-correlated model. Test and worst-case flight thermal analysis with test-correlated model demonstrate minimum 5C margins, except for heater controlled elements which demonstrate a maximum 70% heater duty cycle, and two-phase flow systems which demonstrate a minimum 30% heat transport margin.	1. Thermal analysis with flight-correlated model shows minimum 5C margins for mission trade studies, except for heater controlled elements which have a maximum 70% heater duty cycle, and two-phase flow systems which have a minimum 30% heat transport margin.	1. Thermal analysis with flight-correlated model shows minimum 5C margins for mission disposal options, except for heater controlled elements which have a maximum 70% heater duty cycle, and two-phase flow systems which have a minimum 30% heat transport margin.
Verification:	1. Verify at MCR.	1. Verify worst-case thermal analysis of concept through peer review and at SRR and MDR.	1. Verify worst-case thermal analysis of design through peer review and at PDR.	1. Verify worst-case thermal analysis of detailed design through peer review and at CDR.	1. Verify through peer review and at PER and PSR.	1. Verify thermal analysis of flight system using flight-correlated thermal model through peer review.	1. Verify thermal analysis of flight system using flight-correlated thermal model through peer review.
Revision Status: Rev. E		**Owner:** Thermal Engineering Branch (545)				**Reference:** GEVS 2.63 545-PG-8700.2.1A	

GOLD Rule 4.27 - Test Temperature Margins

4.27	Test Temperature Margins				Mechanical		
Rule: R	Components and systems shall be tested beyond allowable flight temperature limits, to proto-flight or acceptance test levels as appropriate as specified in GEVS section 2.6, which specifies margins for passively and actively controlled hardware. Note that at levels of assembly above component, full specified margins may not always be achievable for all components due to test setup limitations; in these cases, the expected test levels shall be approved by the GSFC Project, and shall be presented at the earliest possible formal review, no later than PER.						
Rationale:	The test program shall ensure that the flight hardware functions properly (meets performance requirements) at temperatures more severe than expected during the mission to demonstrate robustness to meet its mission lifetime requirements. (Note: This rule does not apply to cryogenic systems.)						
Phase:	<A	A	B	C	D	E	F
Activities:	N/A	N/A	1. Component proto-flight thermal vacuum test temperatures shall be specified with the required margin as stated in the Reference (GEVS 2.6).	1. Component, subsystem, and system proto-flight thermal vacuum test temperatures shall be specified with the required margin as stated in the Reference (GEVS 2.6).	1. Components and systems shall undergo proto-flight thermal vacuum testing with the required margin as stated in the Reference (GEVS 2.6). Yellow and Red limits for flight temperature telemetry database shall be consistent with actual proto-flight system thermal vacuum (TV) test temperatures.		
Verification:	N/A	N/A	1. Verify at PDR.	1. Verify at CDR.	1. Verify results of component and subsystem thermal vacuum (TV) tests, and present plans for system TV test at PER. 2. Verify results of system thermal vacuum test at PSR. 3. Verify flight database limits at MRR and/or FRR.		
Revision Status: Rev. E		**Owner:** Thermal Engineering Branch (545)				**Reference:** GEVS 2.6	

GOLD Rule 4.28 - Thermal Design Verification

4.28	Thermal Design Verification						Mechanical
Rule: **R**	All subsystems/systems having a thermal design with identifiable thermal design margins shall be subject to a Thermal Balance Test at the appropriate assembly level per GEVS Section 2.6.						
Rationale:	This test shall provide an empirical verification of the subsystem/system's thermal design margin. In addition, steady state temperature data from this test shall be used to validate subsystem/system thermal math models (TMMs)						
Phase:	**<A**	**A**	**B**	**C**	**D**	**E**	**F**
Activities:	1. Identify thermal balance test concepts.	1. Include thermal balance test in environmental test plan.	1. Identify preliminary thermal balance test architecture and scope.	1. Identify specific thermal balance test architecture and cases.	1. Implement test.	N/A	N/A
Verification:	1. Verify at MCR.	1. Verify at MDR.	1. Verify at SDR and PDR.	1. Verify at CDR.	1. Verify at PER.	N/A	N/A
Revision Status: Rev. E		**Owner:** Thermal Engineering Branch (545)				**Reference:** GEVS 2.6	

GOLD Rule 4.29 - Thermal-Vacuum Cycling

4.29	Thermal-Vacuum Cycling				Mechanical		
Rule: R	All systems flying in unpressurized areas shall have been subjected to a minimum of eight (8) thermal-vacuum test cycles prior to installation on a spacecraft. For an instrument, a minimum of four (4) of these eight (8) Thermal Vacuum cycles shall be performed at the instrument level of assembly.						
Rationale:	This provides workmanship and performance verifications at lower levels of assembly where required environments can be achieved and reduces the risk to cost during spacecraft Integration and Test (I&T). For units where there is an institutional or organizational delivery to an interim level of assembly, pre-delivery testing should include a minimum of 4 cycles.						
Phase:	**<A**	**A**	**B**	**C**	**D**	**E**	**F**
Activities:	1. Identify environmental test concept.	1. Develop preliminary environmental test plan.	1. Update environmental test plan and put under configuration control.	1. Update plan.	1. Implement test cycles.	N/A	N/A
Verification:	1. Verify at MCR.	1. Verify at MDR.	1. Verify at SDR and PDR.	1. Verify at CDR.	1. Verify that all components have seen required testing prior to spacecraft I&T at PER.	N/A	N/A
Revision Status: Rev. E		**Owner:** Applied Engineering and Technology Directorate (500)				**Reference:** GEVS 2.6.2.4.b	

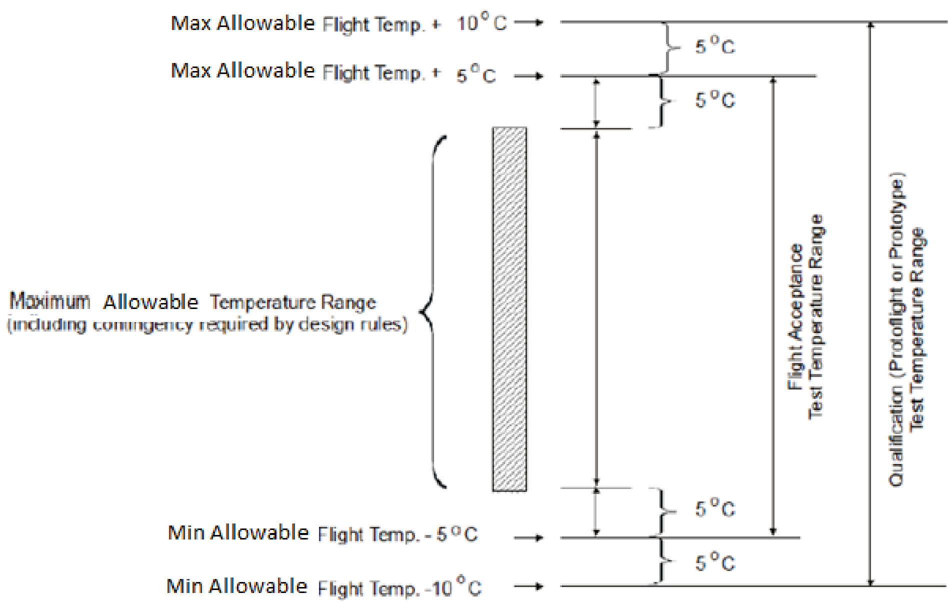
GEVS vs MIL-STD-1540E

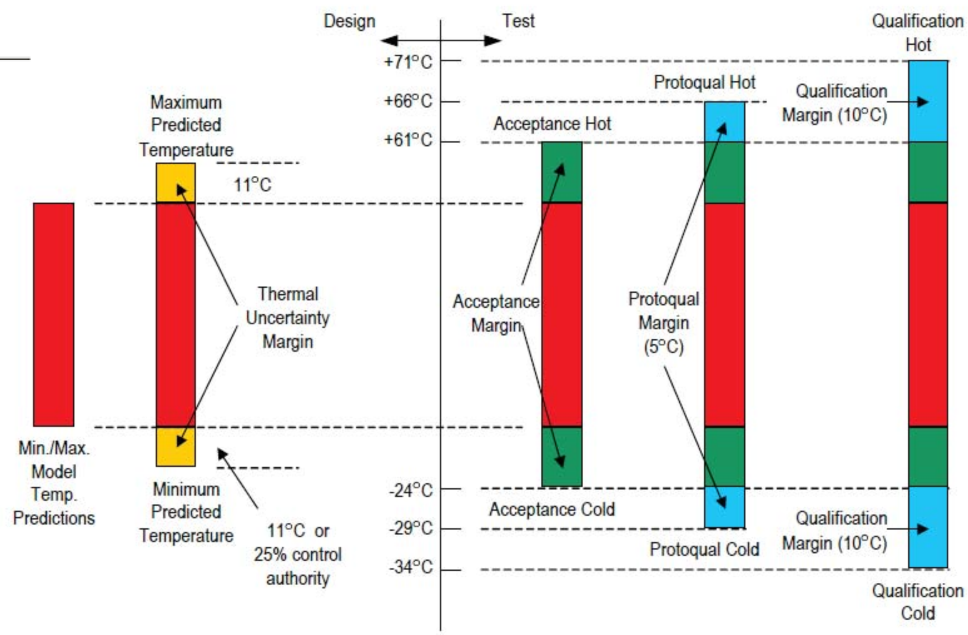
- MIL-STD-1540E Requirements
  - Temperature Ranges
    - Acceptance: maximum predicted or -24C to +61C
    - Protoqualification:5C beyond acceptance or -29C to +66C
    - Qualification:10C beyond acceptance or -34C to +71C
  - Duration
    - Acceptance: 10 TC and 4 TV (14 cycles total)
    - Protoqualification:23 TC and 4 TV (27 cycles total)
    - Qualification:23 TC and 4 TV (27 cycles total)

- GEVS Requirements
  - Temperature Ranges (Typ)
    - Max Predicted: -5 to +45C
    - Operational: -10 to +50C
    - Acceptance: -15C to +55C
    - Protoflight: -20 to +60C
    - Qualification: n/a
  - Duration
    - Accept: 12 TV
    - Protoflight: 12 TV
    - Qualification: n/a

1540 is a robust ESS test.

Margin Comparison GEVS & MIL-STD-1540E





4.0 Test Set-up

- 4.1 Mission Environments
- 4.2 Chambers/GSE
- 4.3 Temperature Sensors/Alarm Limits

Mission Environments

- Before choosing how to simulate your environment, you should first determine what mission environments you are trying to simulate.
- GSFC practice is to simulate worst case (bounding) hot and cold mission environments, and include (at a minimum) operational and survival configurations.
  - Simple geometry spacecraft are more easily determined.
  - Complex external geometry/configuration leads to complex environments due to reflections, solar entrapment, and significant IR backloads.
- Simulating your mission environments correctly is key to a successful thermal balance test.

The goal is to simulate worst case bounding mission environments accurately and in a stable, consistent manner.

Equivalent Sink Temperature

- For any spacecraft surface, there is a single temperature that represents the summation of all external environmental heating sources .This is the "equivalent sink temperature" and is the equilibrium temperature reached by a passive radiating surface when placed in the external environment.
- The equivalent sink temperature includes direct and reflected environments (solar, albedo, IR) and backloading from other SC surfaces. Mathematically based on energy balance:

$$Q_{in,env} = Q_{Out}$$

$$Q_{solar} + Q_{albedo} + Q_{EarthIR} + Q_{backload} = Q_{out}$$

$$Q_{solar} + Q_{albedo} + Q_{EarthIR} = \sigma \sum_{j}^{1,N} Radk_{ij}(T_i^4 - T_j^4)$$

(where surface "i" is the passive radiating surface)

Determining Equivalent Sink Temperature

- Now that we understand the mathematical expression, how do we determine sinks for our mission?

- Evolution of ways used to determine sink temperature:
  - Use absorbed flux data (from thermal models) to calculate
  - Homegrown subroutines that use Q_{ABS} data, RADKs, and temperatures within SINDA.
  - Use surface "patch" near surface of interest (remember the "passive radiating surface" from previous page?)
  - Thermal Desktop TSINK subroutine
  - Post-processing software packages

Absorbed Fluxes

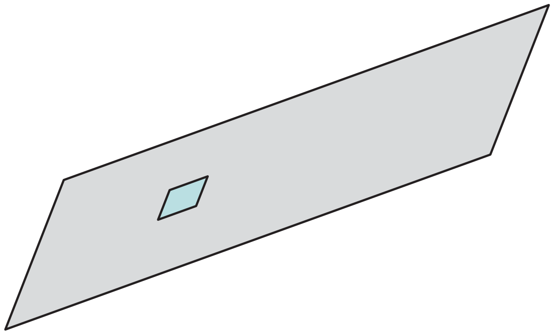
- Use mission HEAT RATE data from thermal model, use absorbed fluxes for primary thermal surfaces of SC (or instrument or unit).
  - Convert to sink temperature

$$\sum \boldsymbol{q}(\boldsymbol{abs}) = \sigma\, \boldsymbol{\varepsilon}\, (\boldsymbol{T}^4 - \boldsymbol{Tsp}^4)$$

- Note that this doesn't include IR backloads, which is included in the thermal solution in the SINDA run.
  - May be accurate enough for surfaces with little backloading.
  - SINDA User subroutines to use HEAT RATE data and RADKs for more accurate sink calculations.

Surface "Patch"

- As discussed earlier, the very definition of equivalent sink temperature is the equilibrium temperature reached by a passive radiating surface when placed in the external environment.
  - Generate a small surface ("patch") just above and having the same thermo-optical properties as the surface you want to find sink temperatures for.
  - Inactive backside.
  - Generate temperature data in SINDA
    - Plot or output temperature data like any other node.

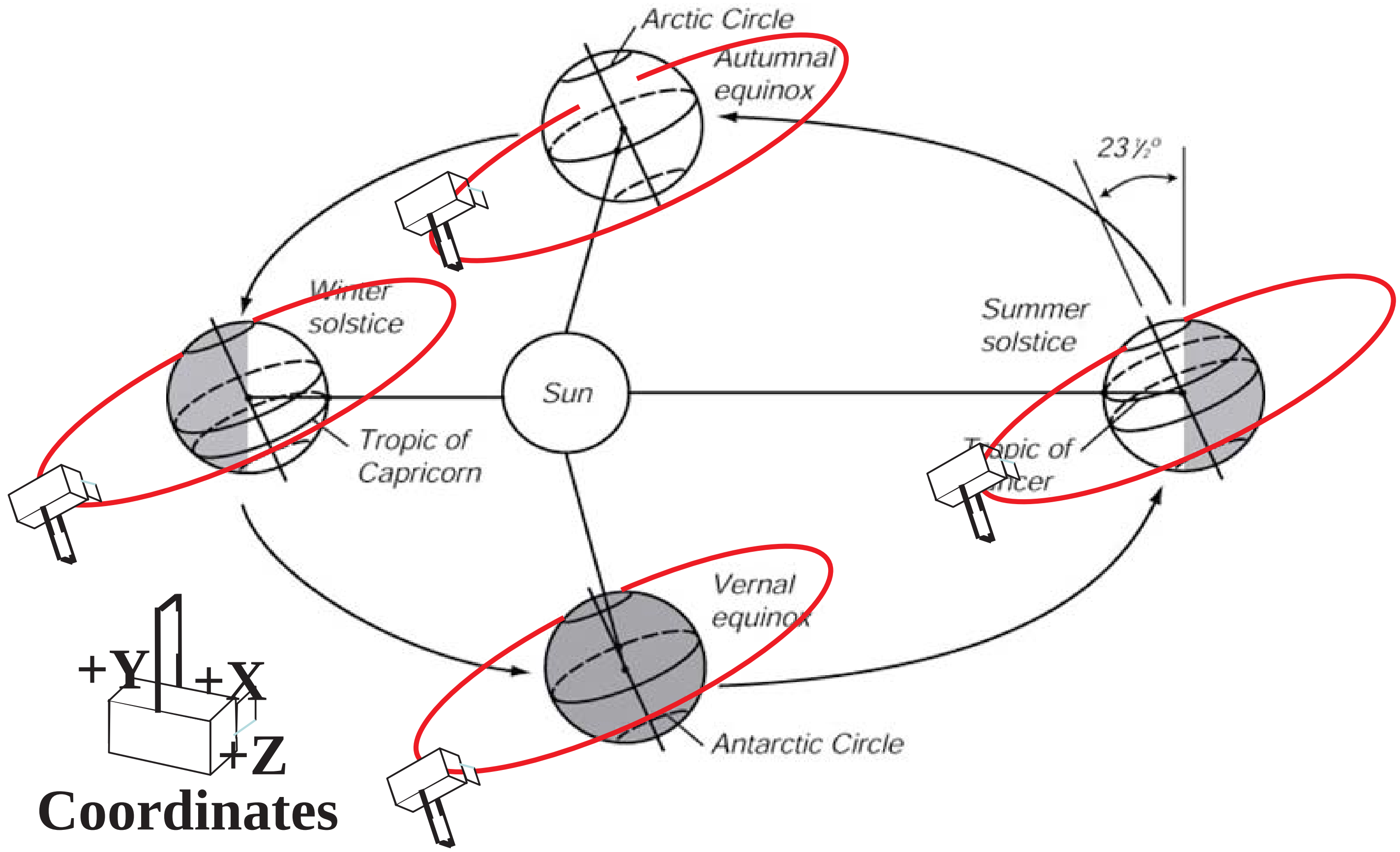


Thermal Desktop TSINK

- TSINK uses Save files in Thermal Desktop, and performs the same function as the TSINK and TSINK1 commands in SINDA/FLUINT.
  - Per the SINDA/FLUINT manual: the sink temperature approximation is normally used (1) to eliminate recalculation of radiative environments in order to speed up parametric sweeps and sensitivity studies, and (2) to enable a designer of a component or subsystem to work independently of a full system model
  - Including or excluding heat rate terms
  - Including only radiative terms, or only linear terms, or both. (Use radiative only for this application)
  - TSINK1 (single node) and TSINK (multiple nodes)

Sink Temperature Example

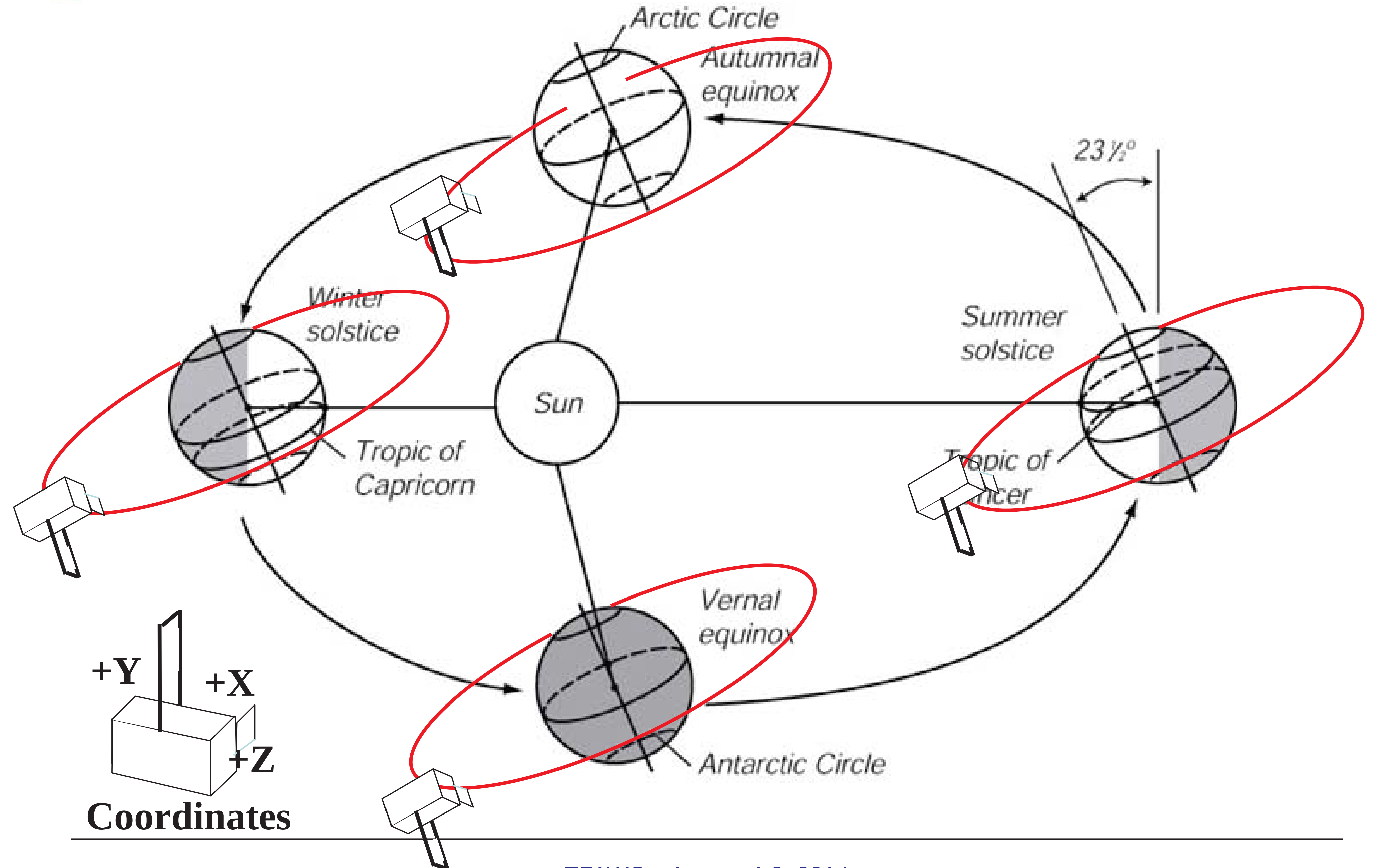
- GOES-R project is geosynchronous weather satellite
  - Large OSR radiators on +/-Y (south & north)
  - Predominantly MLI on +/-X (east & west) and +/-Z surfaces (nadir & zenith)



Sink Temperature Example

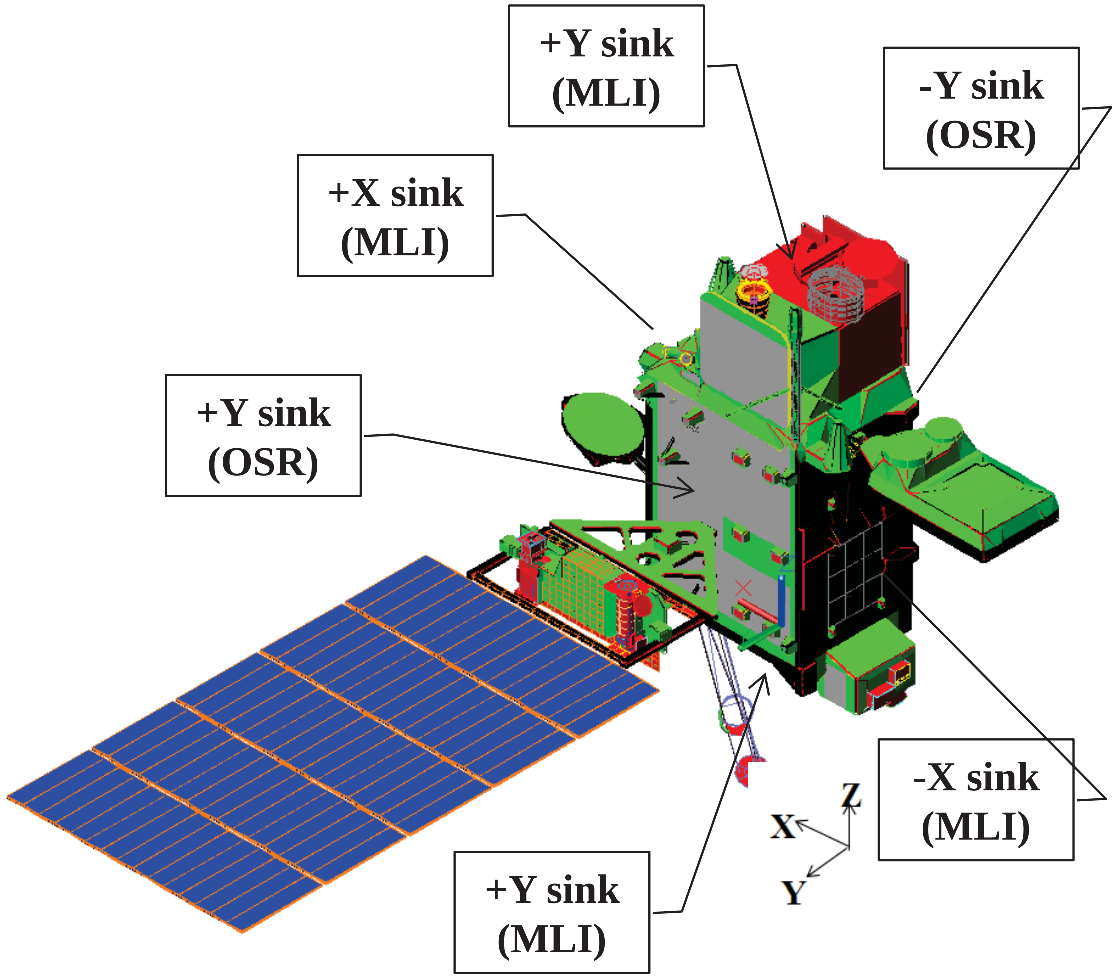
- For a geosnychronous communications satellite, with seasonal ecliptic declination resulting in +/-23.5° solar incident angle on the North/South radiators, resulting in worst hot case direct solar loading of 115 and 126 W/m^2 on the north and south radiators, respectively. (The difference is the solar intensity variation between SS and WS).
- Typically, bounding hot & cold environments are:
  - Hot:
    - Winter Solstice: max sun angle on south side, max SOL
    - Summer Solstice: max sun angle on north side, high SOL
  - Cold:
    - Equinox: no sun on north/south, min SOL
- Neglecting any reflections or IR backloading, these fluxes on OSRs result in equivalent sink temperatures of:
  - 115 W/m^2: -48°C
  - 126 W/m^2: -42°C

Geosynchronous Environment

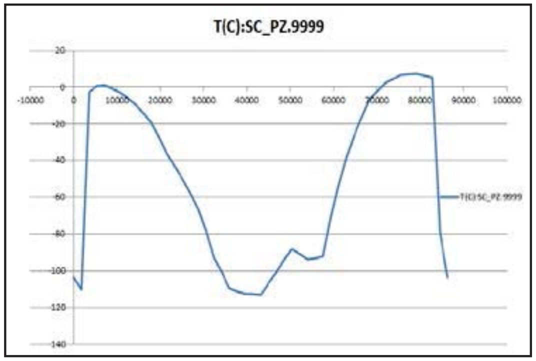


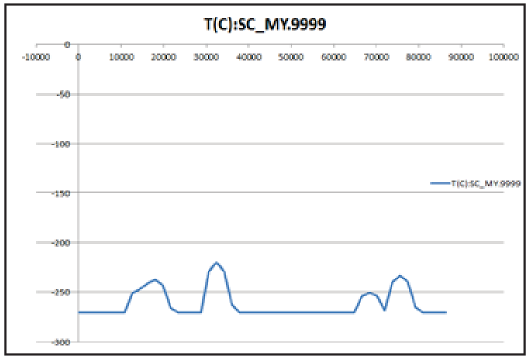
GOES-R Example

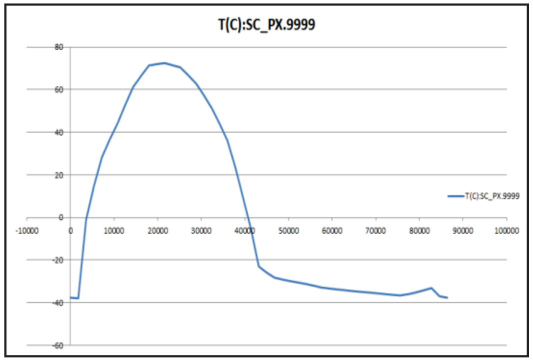
- Flight sink temperatures driven by OSR and MLI surfaces
  - OSRs are primary thermal control coating.
  - +/-X and +/-Z sinks (fluxes) are highly transient in all cases.
- Started with hand calculations
  - Grossly correct, but appendage effect not so easy.
- Also used "patch" surfaces and TSINK subroutine.

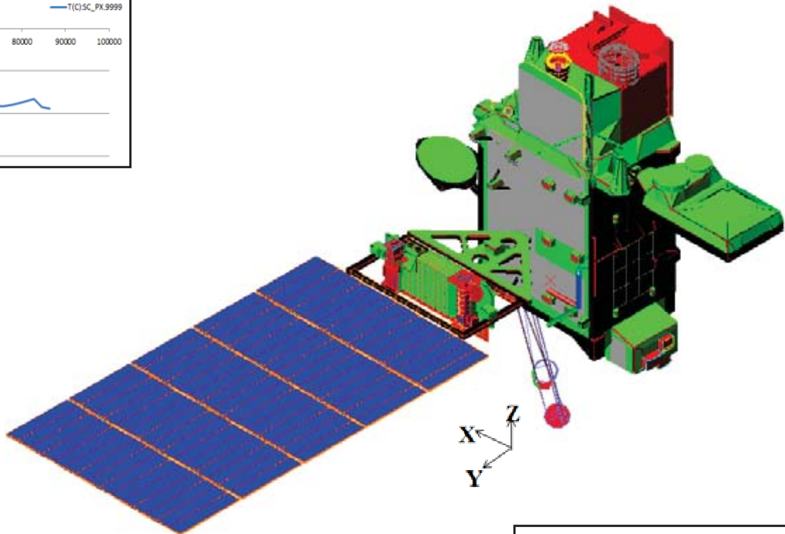


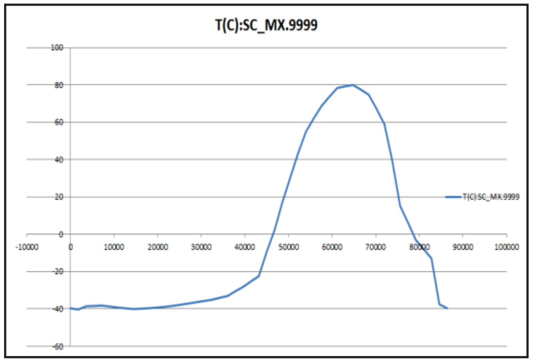
GOES-R Sink Temperatures (AEBOL)

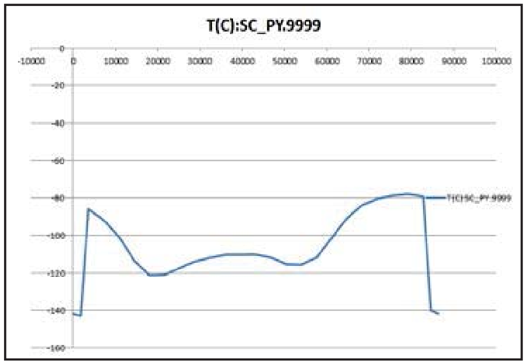


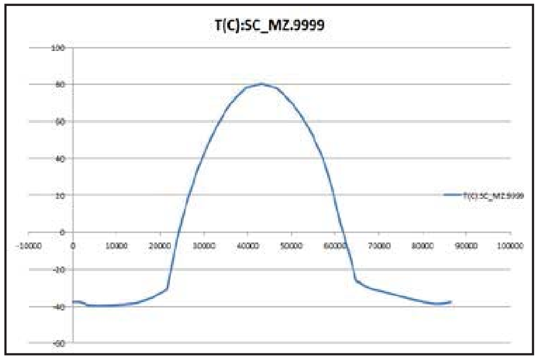




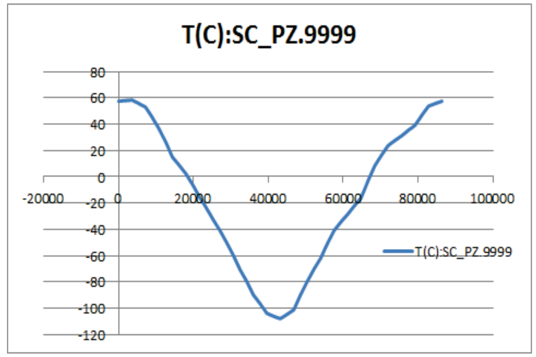


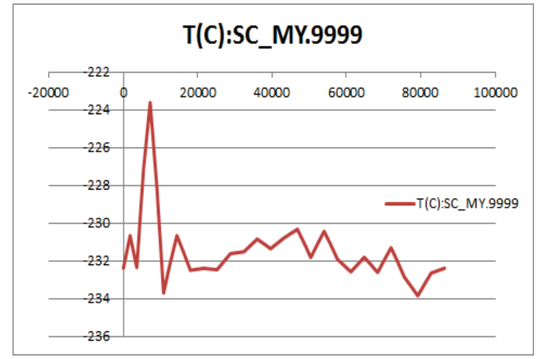


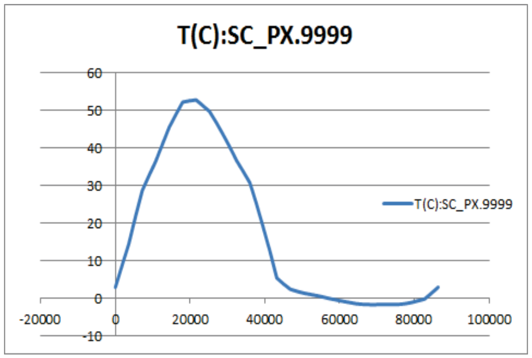


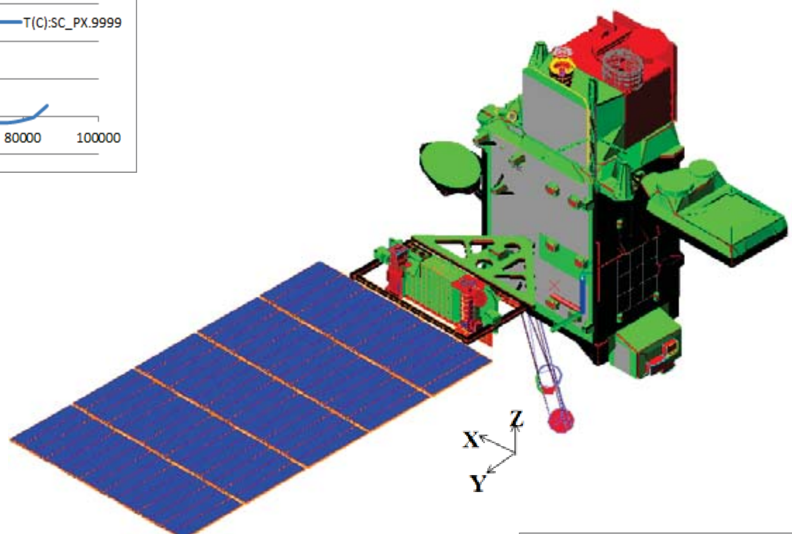


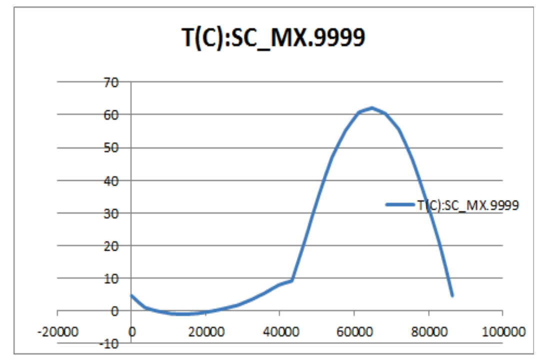
GOES-R Sink Temperatures (WSEOL)

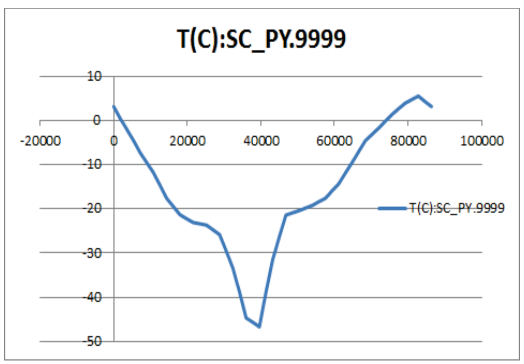


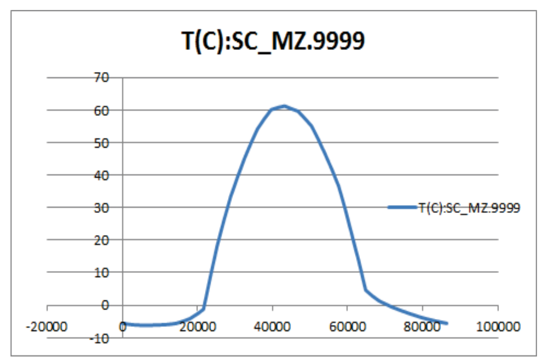




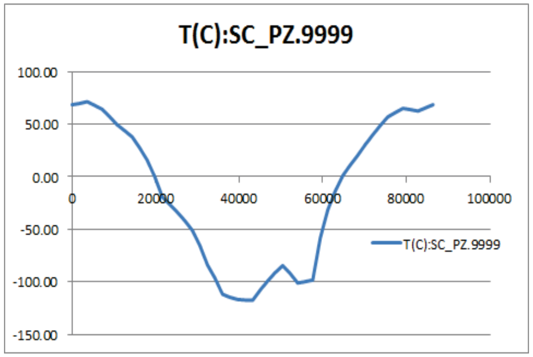


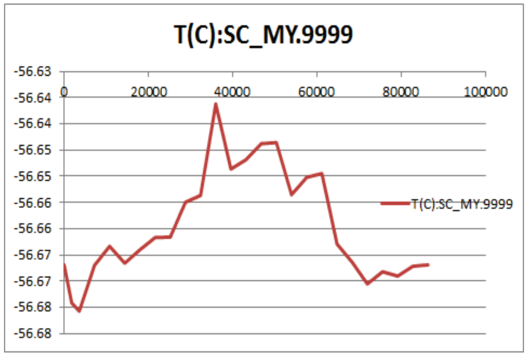


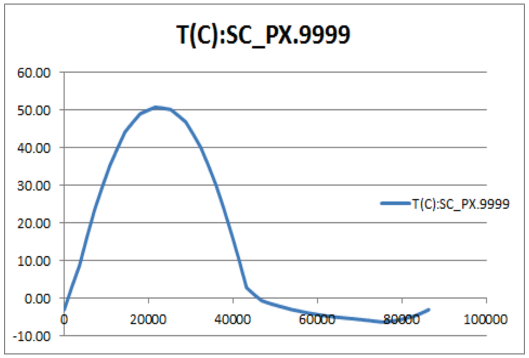


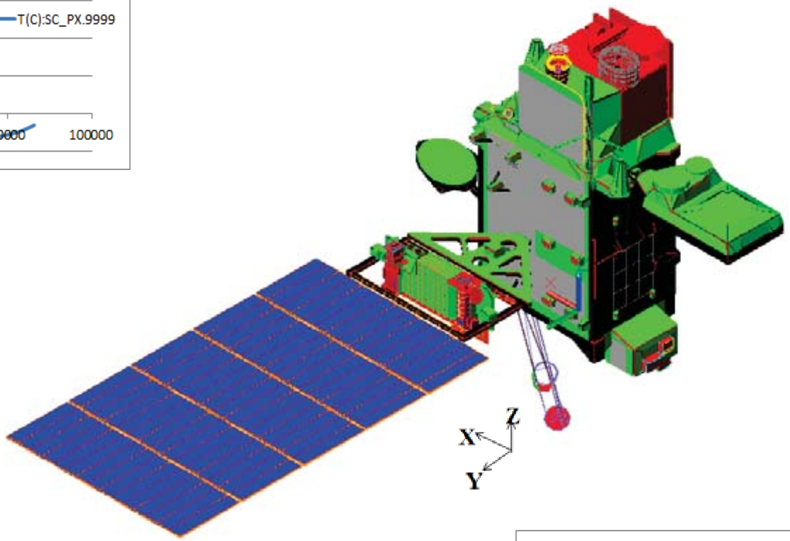


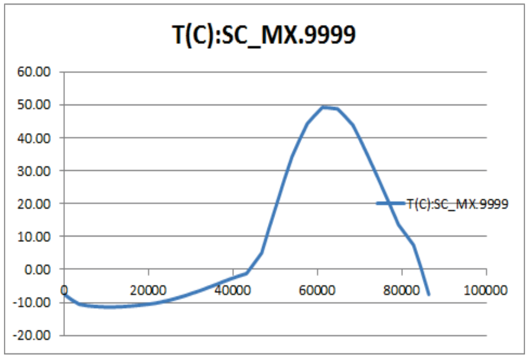
GOES-R Sink Temperatures (SSEOL)

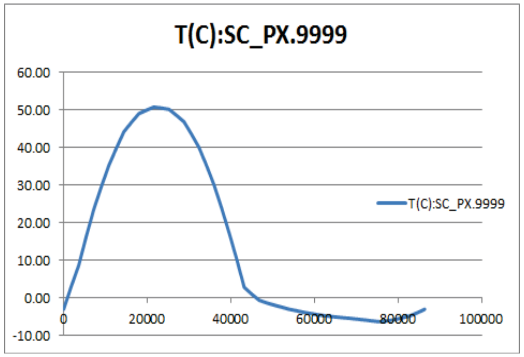


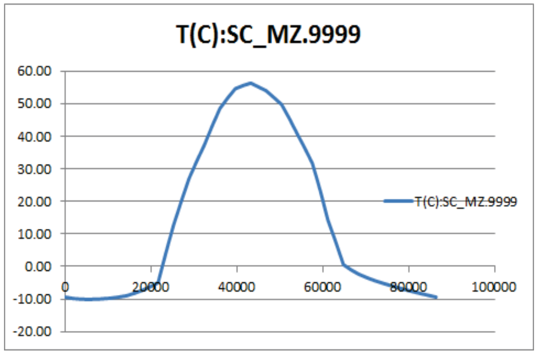












GOES-R Sinks - Summary

- TSINK results used to determine equivalent sink temperatures for the mission.
- As seen in the plots, the orbit average of the +/-X and of the +/-Z sinks is “not that different”, so “sun averages” are being planned for hot cases and “orbit average” used for AEBOL sinks.

	SSEOL (°C)	WSEOL (°C)	AEBOL (°C)
MX (west), MLI	Sun Avg	Orb Avg	Orb Avg
PX (east), MLI	Orb Avg	Sun Avg	Orb Avg
MY (north), Rad	Orb Avg	Orb Avg	Orb Avg
PY (south), Rad	Orb Avg	Orb Avg	Orb Avg
MZ (zenith), MLI	Sun Avg	Orb Avg	Orb Avg
PZ (nadir), MLI	Orb Avg	Sun Avg	Orb Avg

	SSEOL (°C)	WSEOL (°C)	AEBOL (°C)
MX (west), MLI	-8	22	-2
PX (east), MLI	14	33	2
MY (north), Rad	-57	-175	-175
PY (south), Rad	-102	-16	-104
MZ (zenith), MLI	34	18	5
PZ (nadir), MLI	-14	59	-37

Thermal Balance Stability Criteria

- Thermal Balance testing is actually an "Energy Balance" test.
- How stable does YOUR test need to be ?
- GEVS sez " 0.05°C/hour for 6 hours", or a 2-5% energy balance. What is that ?
  - Energy balance:
    - $Q_{IN} = Q_{OUT}$
    - $\% * Q = M * C_P * dT/dt$
- Applying this overall, or (better yet) for "thermally separate areas" of your Test Article will optimize the transition time while meeting stability requirements.
- Examples: ((assume C_P = aluminum)
  - 100kg SC w/100W => dT/dt: 0.015°C/hour
  - 400kg radiator w/units @1200W => 0.05°C/hour
  - 5000kg SC w/3000W => dT/dt: 0.009°C/hour
- If heater controlled, then <2-5% change in duty cycle.
- But must still watch parts buried deep within the SC (Prop tanks, structure, etc)

Tailored Thermal Balance Criteria

TCS Control Zone	Power, Q Watts (J/s)	Mass, M kg	Specific Heat, Cp J/kg-°C	Stability dT/dt °C/hr	Total Energy Balance Percentage %
Spacecraft Deck					
- Bay #1 (Navigator+USO)	38.41	21.37	879.00	0.25	3.40%
- Bay #2 (Battery)	1.00	27.46	879.00	0.005	3.35%
- Bay #3 (F/D)	1.00	1.00	879.00	0.15	3.66%
- Bay #4 (Comm)	26.90	14.36	879.00	0.25	3.26%
- Bay #5 (C&DH)	24.61	23.26	879.00	0.15	3.46%
- Bay #6 (Star Sensor)	10.88	8.41	879.00	0.15	2.83%
- Bay #7 (Misc)	1.00	1.00	879.00	0.15	3.66%
- Bay #8 (PSEES)	35.94	36.96	879.00	0.15	3.77%
Spacecraft Deck SubTotal	139.74	133.81	879.00	0.15	3.51%
Instrument Deck					
- Bay #1 (+X DIS/DES)	11.60	11.88	879.00	0.125	3.13%
- Bay #2 (CIDP)	19.70	17.01	879.00	0.125	2.64%
- Bay #3 (+Y DIS/DES)	11.60	11.88	879.00	0.125	3.13%
- Bay #4 (IDPU/EDI/EIS/SDP)	14.68	20.44	879.00	0.125	4.25%
- Bay #5 (-X DIS/DES)	11.60	11.88	879.00	0.125	3.13%
- Bay #6 (SDP/HPCA/ASPOC)	13.06	23.40	879.00	0.1	4.37%
- Bay #7 (CEB,-Y DIS/DES)	22.94	22.85	879.00	0.125	3.04%
- Bay #8 (SDP, EDI)	4.09	15.96	879.00	0.05	4.77%
Instrument Deck SubTotal	109.26	135.31	879.00	0.125	3.78%
Propulsion System					
- Propulsion Tank Bay #2	20.00	12.10	879.00	0.25	3.69%
- Propulsion Tank Bay #4	20.00	12.10	879.00	0.25	3.69%
- Propulsion Tank Bay #6	20.00	12.10	879.00	0.25	3.69%
- Propulsion Tank Bay #7	20.00	12.10	879.00	0.25	3.69%
- CSA Bay #1-3	10.00	3.36	879.00	0.45	3.69%
- CSA Bay #3-5	10.00	3.36	879.00	0.45	3.69%
- CSA Bay #5-7	10.00	3.36	879.00	0.45	3.69%
- CSA Bay #7-1	10.00	3.36	879.00	0.45	3.69%
Thrust Tube, ODS and Gold Plated Rings					
- +Z ODS and Rings	100.00	30.66	879.00	0.5	3.74%
- Thrust Tube	50.00	82.64	879.00	0.125	5.04%
- -Z ODS and Rings	100.00	30.66	879.00	0.5	3.74%
Observatory Total	619.00	474.91	879.00	0.200	3.75%

4.0 Test Set-up

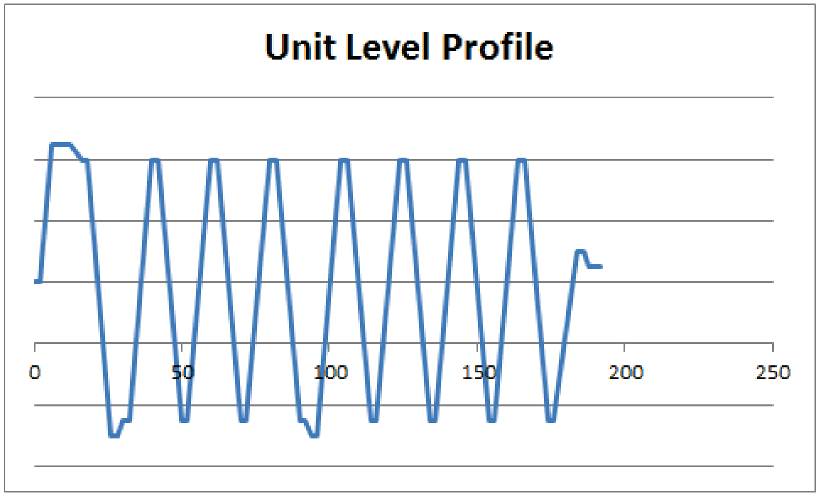
- 4.1 Mission Environments
- 4.2 Chambers/GSE
- 4.3 Temperature Sensors/Alarm Limits

Test Chamber Capability

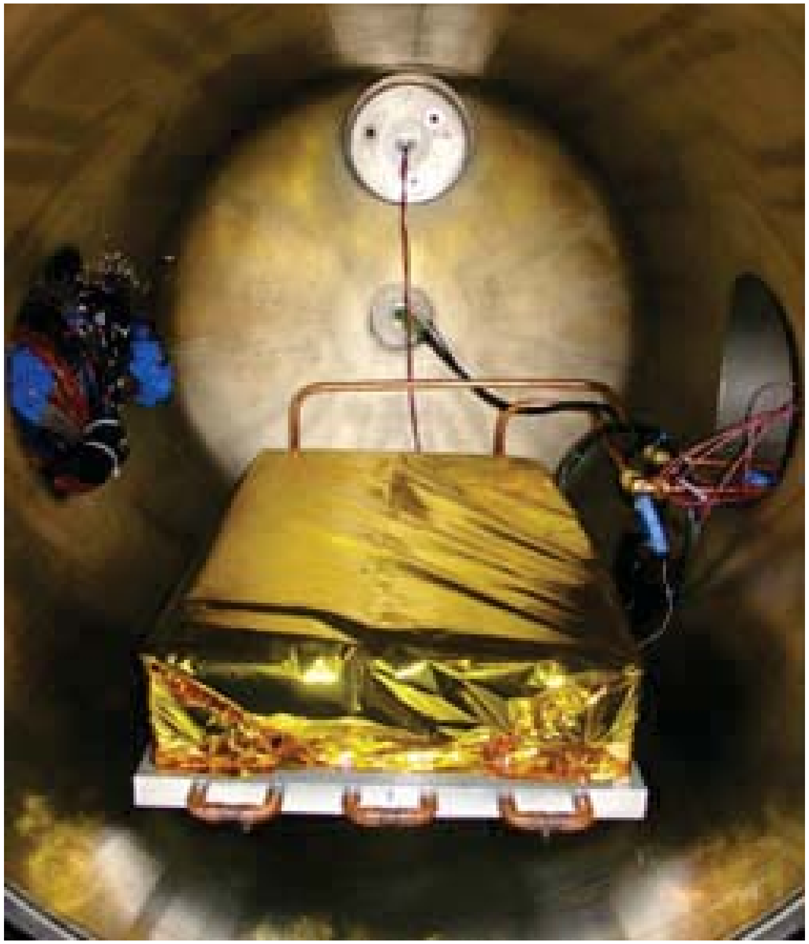
- Know your chamber capabilities early in your test planning.
- Environmental simulation
  - Temperature capability, GN_2 / LN_2, total heat load
  - Vacuum levels
- Data Systems
- Test Sensors
- Power Supplies
- Understand the test orientation in the design phase to make sure heat pipes operate

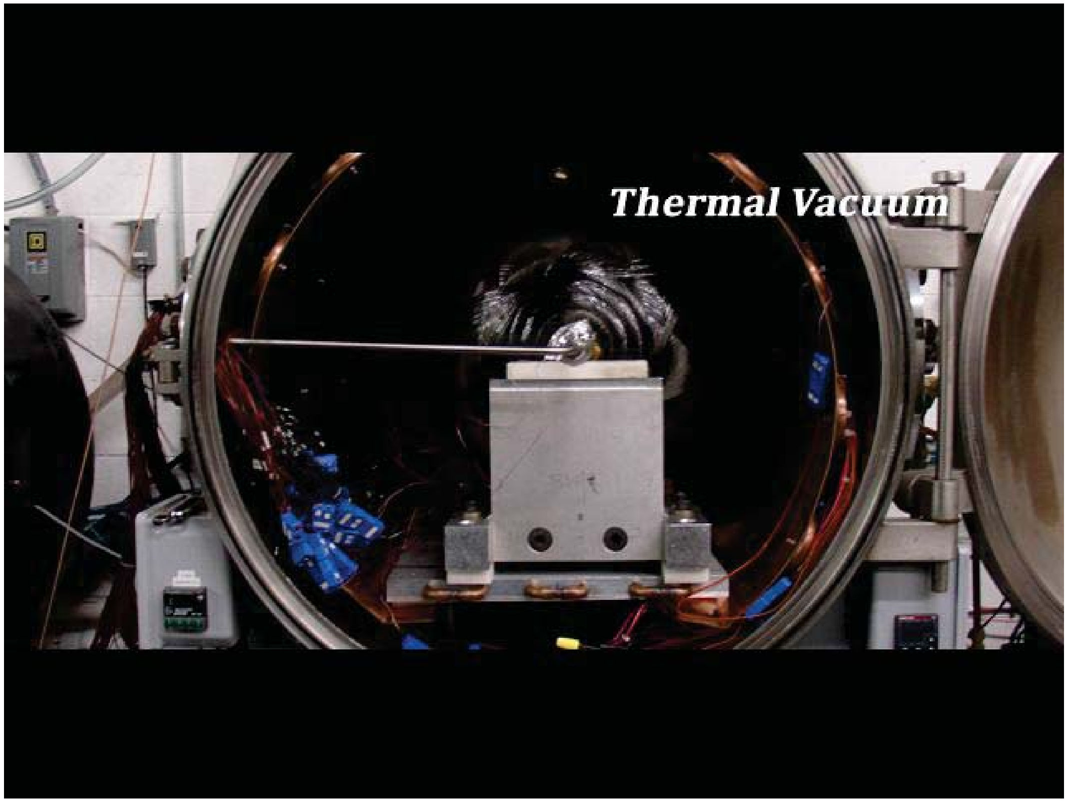
Test Flow - Unit

- Unit level verification testing includes performance testing at required temperatures and Environmental Stress Screening.
  - Performance testing at hot and cold temperature extremes (Side A/B)
  - Functional testing during all transitions (the box stays ON)
  - Hot and cold starts
  - Units are cycles between hot and cold extremes while operating.
  - Electronics: typically temperature controlled platen, with ambient or controlled radiative sink
  - Mechanisms: lamps, heaters, controlled radiative sink
- Although thermal balance plateaus are usually not explicitly included, there is usually sufficiently steady operations and data to correlate the unit level thermal models using flight telemetry or test sensors.



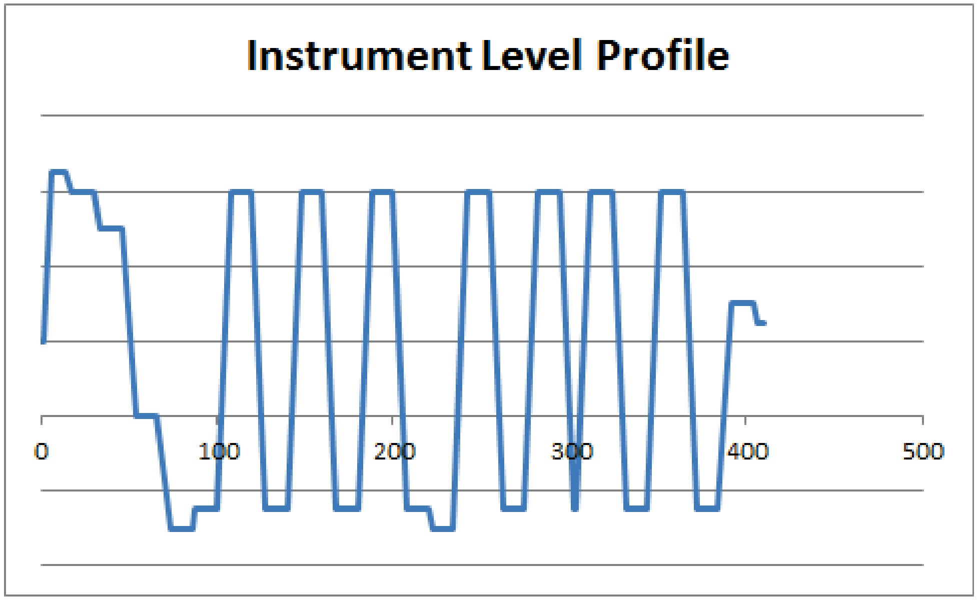
Photos– Unit Level





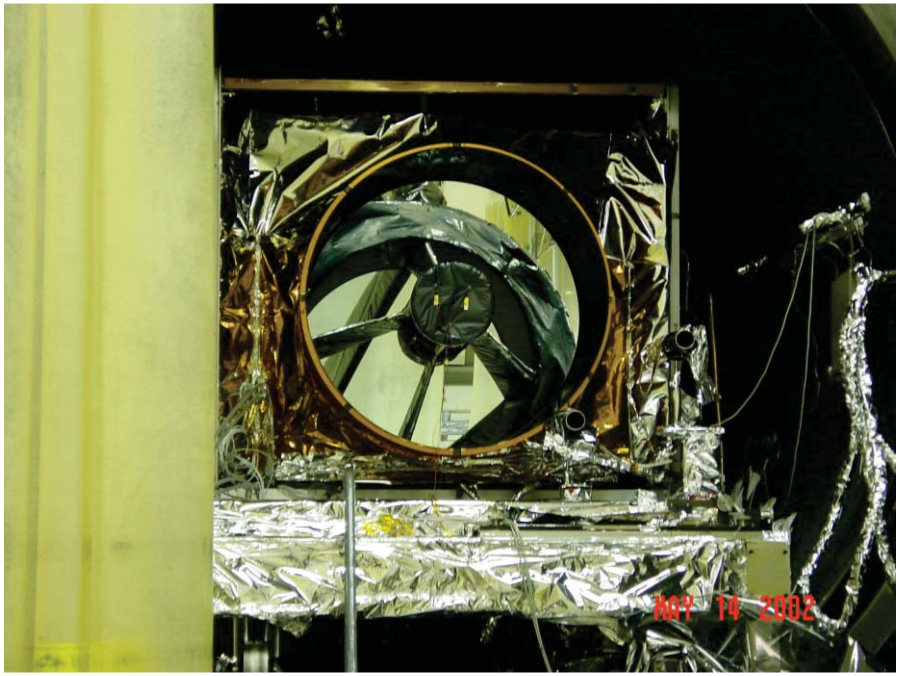
Test Flow - Instrument

- Types of thermal testing, includes qualification, engineering development, life test, and verification testing.
- For subsystem/instrument and spacecraft level testing, there are usually two types of thermal verification tests:
  - Thermal Balance:
  - Thermal Vacuum Cycles:



- Typically very unique requirements for different types of instruments. Besides the usual radiative zones w/temperature controlled I/Fs:
  - Optical/lasers: extensive OGSE in chamber
  - IR: Passive cryo requires very cold sinks (LN_2 or maybe LHe)
  - Heat pipe orientation
- For some tests, removing the MLI following balance testing is done to enhance transitions to the cycles plateaus.
- Almost always deliverable reduced thermal models to SC and LV analysis, so correlation and model reduction is critical.

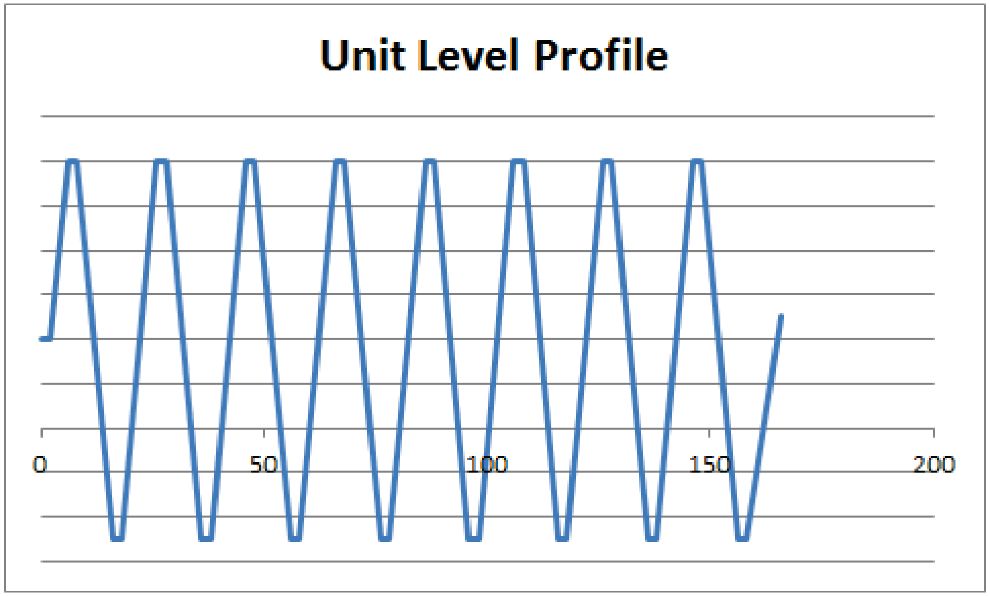
LAT @ NRL

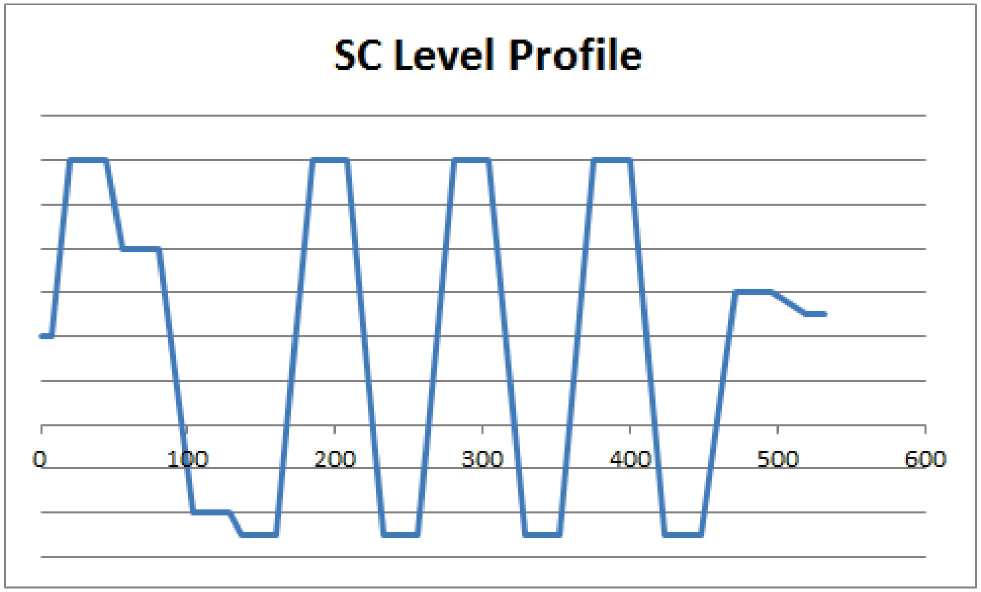


GLAS @ GSFC

Test Flow – Spacecraft/Observatory

- Unit level testing
  - 8 cycles to protoflight
- Instruments
  - 8 cycles to protoflight (or 4 unit/ 4 instrument)
- SC level
  - 4 cycles to protoflight
- Thermal balance plateaus are usually done at the beginning of the test to allow an assessment of the accuracy of the model prior to performing the cycles at plateau temperatures.





Environmental Simulation – SC Level

- Spacecraft: Radiative zones w/temperature controlled I/Fs
  - Usually "near ambient", but cryo shroud/targets usually needed.
  - Real challenges like JWST (<40°K) and missions to outer/inner planets exist too. [play JWST chamber video]
- Heat pipe orientation

MMS @ NRL

Russian Grunt @ NITs RKP

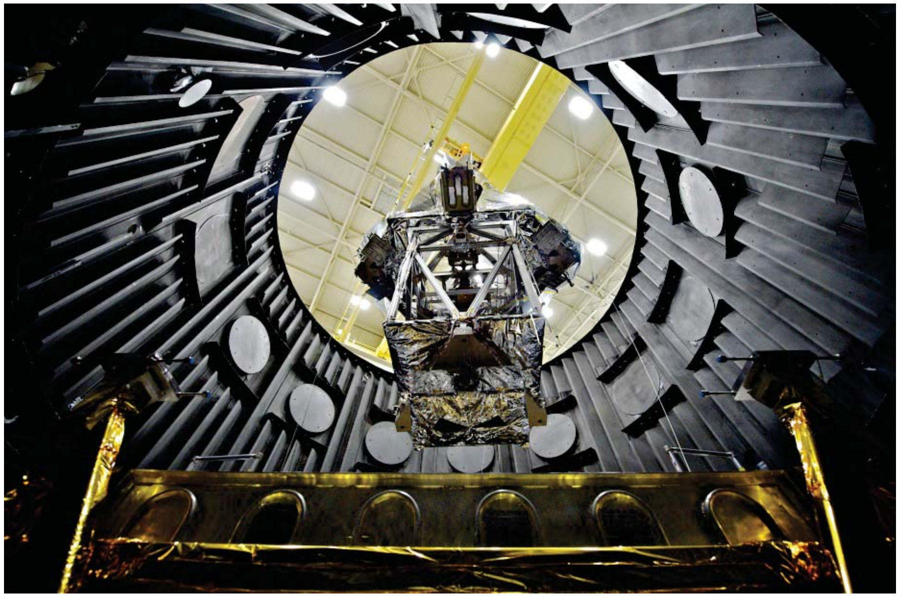
Thermal Vacuum Chambers

LCROSS @ NGAS

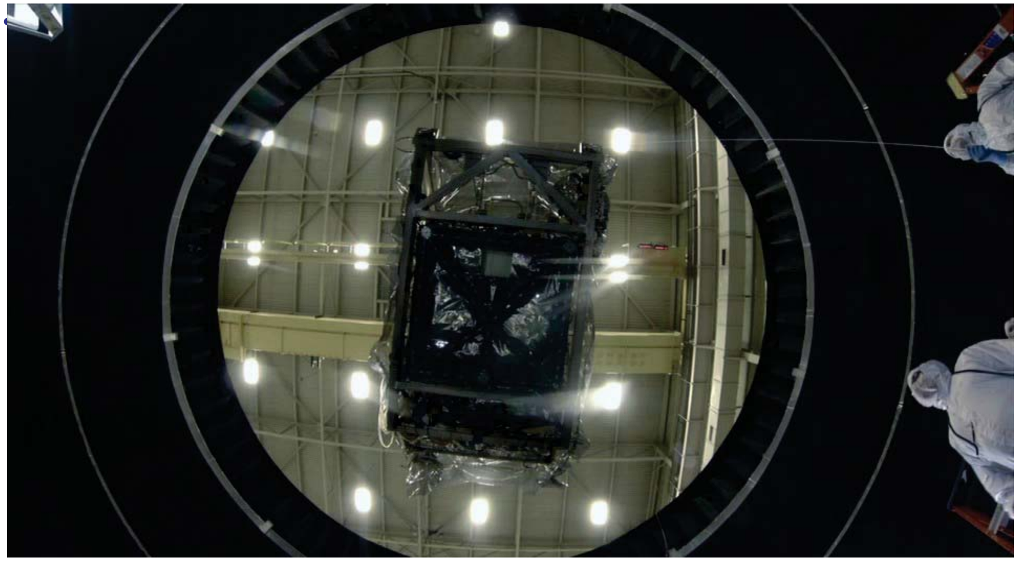
SAC-D Argentina

Space Environment Simulator (SES)

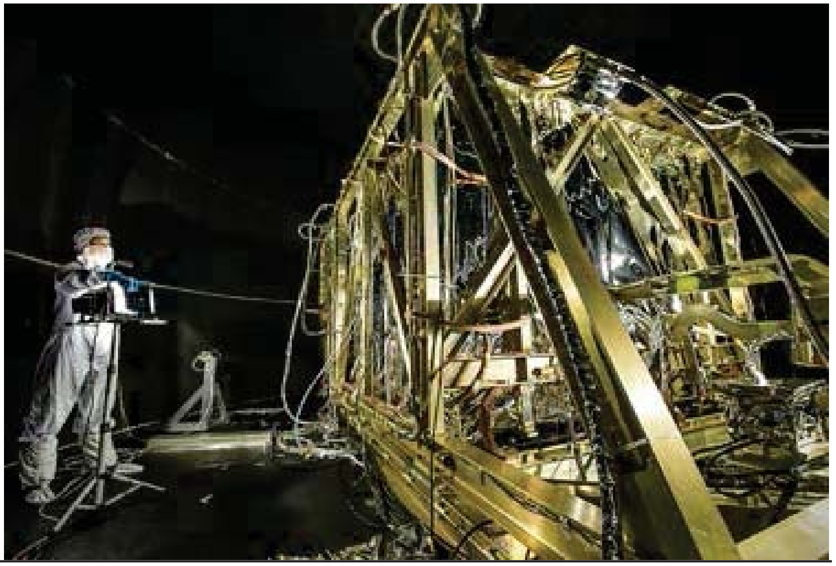
- Test pressure: 13.3 μpa (10-7 torr)
- Shroud temperature:
  - GN2 mode: -130°C to 100°C (-202°F to 212°F)
  - LN2 mode: -180°C (-292°F)
- Chamber pumping speed:
  - 8 cryopumps: 2.4 x 105 lit/sec (5.1 x 105 cfm) @ 133 μpa (10-6 torr)
  - Turbomolecular pump: 6,000 lit/sec (12,700 cfm) @ 133 μpa (10-6 torr)
- PHYSICAL CHARACTERISTICS:
  - Test volume: 8.23m diameter x 12.19m H (27' x 40')
  - Payload support: 9,072 Kg (20,000 lb)
  - Removable floor: 11,794 Kg (26,000 lb)
  - Viewports: 30 cm (12") two each
  - Std. electrical feedthroughs: 37-pin, 7-pin, 4-pin, RF
- WF3 video
- MAVEN into chamber
- RBSP into TV Chamber



GPM



ISIM



ISIM

Grab Your Popcorn

- WF3 video
- RBSP into TV Chamber
- JWST in Chamber A

- GPM into Tvac
- MAVEN into chamber

- TIRS in TVac

Environmental Simulation

- Environmental control must be able to accurately simulate the desired mission environments (for thermal balance).
  - Typically done with external targets of various types, but sometimes heaters on hardware are used.
  - Electrical heaters, IR "targets", and solar simulators are the 3 primary means of environment simulation in thermal vacuum testing.
  - The selected method should be the same for balance and to achieve protoflight temperatures (for thermal cycles).
- Whatever method is used, care must be taken:
  - To ensure correct simulation of mission environments
  - To allow protoflight temperatures to be achieved during subsequent thermal vacuum cycling
  - To ensure adequate cooling to reach cold limits or excessive transition times depending on the size of the plates and test article dissipations.

Environmental Simulation - IR

- Predominantly, mission environments are simulated using IR targets.
  - Black painted plates (with heaters and temperature controlled) are probably most common method used.
  - IR targets can simulate the total heat flux onto a satellite, but can not simulate the collimation and spectral characteristics of solar irradiance.
- IR
  - GN_2 or LN_2 coldplates: can be used to establish warm or cold sinks. Cold flushing helps with hot-cold transitions.
  - Heater plates: Most simulations use IR plates/sources. With only radiative cooling to cold shroud, hot-cold transitions are longer.
  - Quartz lamps: tubular bulbs singular or arranged in array
  - Cal rods: tubular ceramic heaters arranged in an array to provide relatively smooth sink.

Environmental Simulation – Solar Sim

- Solar simulation can not simulate the planetary IR loading.
- Few facilities in the U.S or elsewhere; especially for large test articles (spacecraft).
- Benefit of reflections, etc for orbit simulations. True orbit simulations possible, but requires complex facility versus static (fixed) position.
- Assess possible sink simulation types, considering:
  - Cost, facility limitations, contamination, etc

Test Sinks – IR Heater/Controlled Plates

- Predominant method of simulating sink in thermal vacuum testing.
- Temperature control provided by:
  - Heaters on plate and radiative cooling from backside to chamber shroud.
  - Heaters on plate with LN_2 or GN_2 (or other) flowing through plate.
- Thermal balance and cycle hot plateaus usually a matter of providing enough heater power while radiating to an colder shroud.
- Temperatures achievable in cold plateaus (balance and cycles) may be limited since plates act as a barrier to direct radiation to the chamber shroud. Discrete coldplates allow cooling of the targets to achieve cold temperature goals.

$$\overbrace{\underbrace{Q_{solar}+Q_{albedo}+Q_{EarthIR}}_{Q_{env}}+(\underbrace{Q_{backload}}_{\sigma\sum_{j}^{1,N}Radk_{ij}T_j^4}-\underbrace{Q_{Out,Surface}}_{\sigma\sum_{j}^{1,N}Radk_{ij}T_i^4})}^{\text{Energy balance of spacecraft in flight}}=\overbrace{\underbrace{Q_{Sink}-Q_{Out,Surface}}_{\sigma\sum_{j}^{1,N}Radk_{ij}(T_{i,Sink}^4-T_i^4)}}^{\text{Energy balance of spacecraft in test}}$$

Thermal Conditioning Units (TCUs)

- Use of GN_2 to provide temperature control of IR targets inside TV chamber require thermal conditioning outside the chamber.
- Typical applications for these units include independent thermal control of test articles and contamination monitoring devices such as mirrors and TQCMs.
- Chamber penetrations are configured to accommodate the thermal conditioning units.

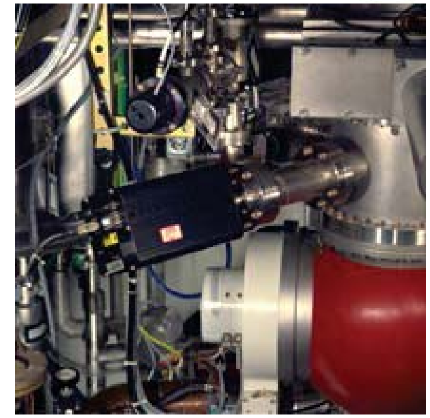
Facility No.	Temp Range	Heating Cap. (watt)	Cooling Cap. (watt)	Size (H x W xD)	MFR	Notes
201	-140 to 140° C (-220 to 284° F)	1,400	1,000	1.8m x 0.97m x 1.7m (5.9' x 3.2' x 5.6')	CVI	
205	-100 to 100° C (-148 to 212° F)	500	500	0.89m x 0.51m x 0.51m (2.9' x 1.7' x 1.7')	Slack	1
207	-100 to 100° C (-148 to 212° F)	300	300	0.38m x 0.38m x 0.38m (1.3' x 1.3' x 1.3')	Slack	1
230	-150 to 150° C (-238 to 302° F)	12,000	10,000	2.1m x 0.81m x 2.1m (6.8' x 2.7' x 6.8')	DynaVac	

Heater Controllers

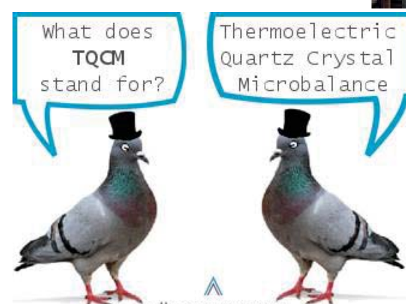
- Small chambers may need only a couple of power supplies to provide power to a few heaters in the tests.
- Larger and more complicated spacecraft and instrument thermal vacuum testing facilities today employ multiple racks of power supplies to provide power to the many non-flight heaters used in these tests.
- Typical parameters:
  - Temperature: -200 to +200°C (-328 to +392°F)
  - Heater zones: 12 channels
  - Heater power: 600 watts per channel (0-150 volts DC @ 0-4 amperes)
  - Modes: Temperature controlled, constant power, zero-Q
  - Temperature sensors: Type T thermocouples

Contamination Monitoring

- Contamination control is key for satellites – even more so for those with scientific instruments sensitive to contamination from molecular outgassing onto critical optical or thermal surfaces.
  - RGA: Residual Gas Analyzer – used to measure the partial pressures of ionized molecules over a mass range of 1 to 200 atomic mass units (AMU). Oriented to maximize the detection of the outgassing species and activated after the facility pressure reaches 10-4 torr.



  - TQCM: Thermoelectric Quartz Crystal Microbalance measures and records condensable masses (outgassing) that deposit on a piezoelectric crystal which changes frequency proportionally to the amount of payload outgassing. Turned on <10-5 torr.

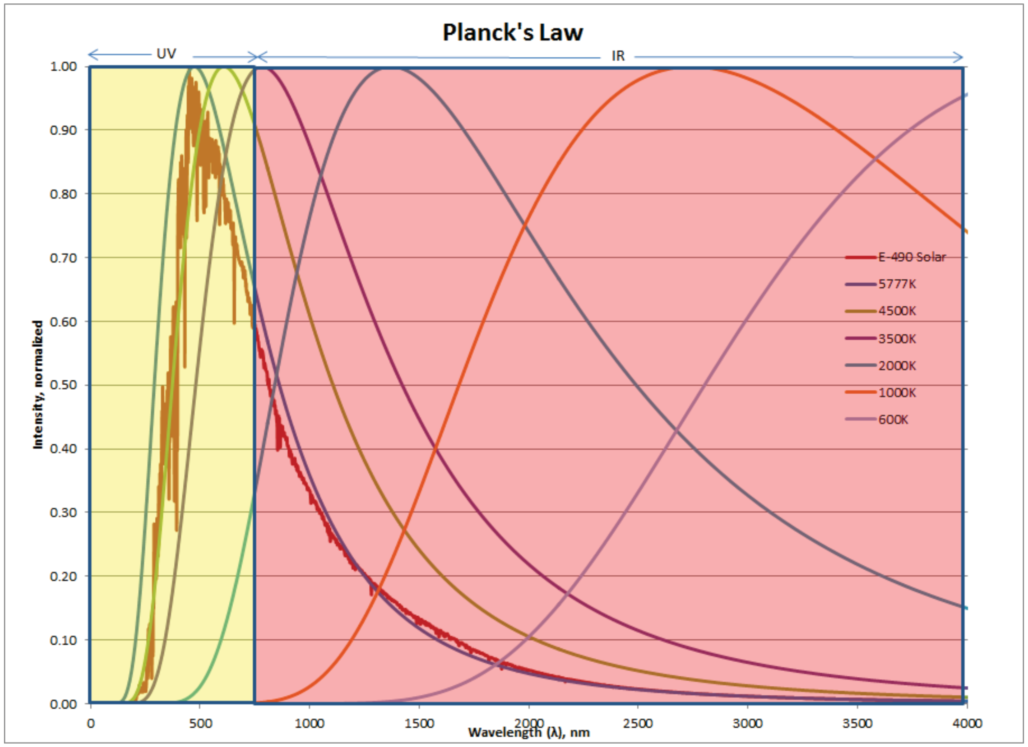


  - Cold Finger (CF): Condensable vapors are collected by the cold finger and analyzed after the test. In some cases, a large cold plate is used to collect the condensable materials.
  - The cold finger is maintained at LN2 temperature during test, rinsed with IPA and analyzed after the test.

  - CCMs – Contamination Control Mirrors are used in the thermal vacuum chambers; however, they may be placed anywhere to collect condensable matter.

IR Lamps

- Typical tungsten filament within quartz glass shell.
- Can be used for all levels of testing (unit, instrument, SC)
  - mechanism testing where movement precludes mounting a heater
  - arrays for radiator (subassembly testing)
  - Small size would require large, complex arrays for most SC testing, but it is possible.
- These are very similar to the next IR method to be discussed, so........

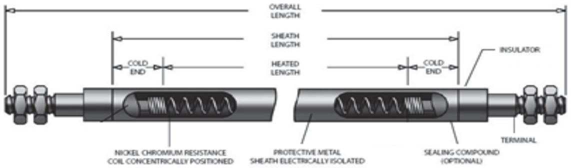


- Spectral energy changes over temperature. These lamps can be very hot ($T_{FILAMENT}$ >4000°C) at high power.
- At that temperature distribution is mostly UV.
- Requires sink detector

IR – "Cal rods"

- Tubular heaters were developed for appliances & materials processing industry. Uses include:
  - Kitchen ovens
  - Industrial process control
  - Liquid immersion heating

- Numerous vendors available. Note that CalRod® is one vendor's trademark name. All use resistance wire potted (various materials) and encased inside a tubular, metallic sheathing (various materials). Various end fitting (terminal configurations) also available.



Cal Rods – Pros & Cons

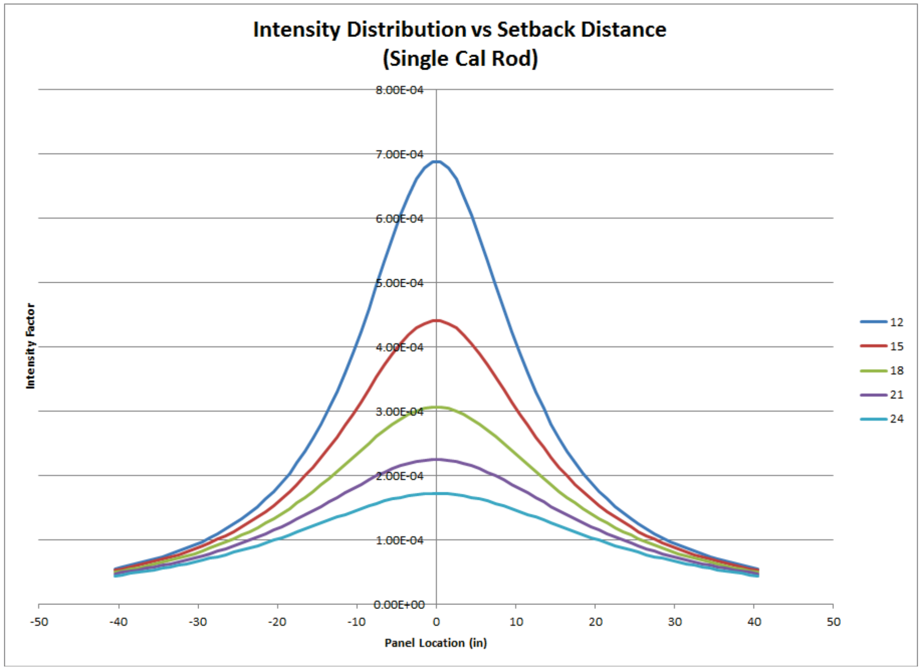
- Long length available makes using them with large test articles simpler than IR lamps. This concept also utilizes the radiative view to the cold chamber shroud COMBINED with the local heating from these small diameter tubular heaters.
- These things do get hot – typically 600C is the realistic limit, although they are rated much higher…..you get into contamination issues, power supply issues, etc.
  - Planck's Law shows at 600°C, these remain in the IR regime, unlike the IR lamps discussed earlier.
- They also allow the equivalent sink to cool rapidly when they are turned off, providing transient sink capability, if desired.
- Since the goal is to provide a relatively isothermal sink, spacing and setback are key parameters to consider. Some data is presented on the following slide, but I encourage you to perform your own calculations.
- Most importantly, special monitors are needed to verify sink temperatures achieved. Although given many names, I call them "Equivalent Sink Detectors" or ESDs.

Cal Rod Basics

- For a given power level (voltage setting) the intensity (I) of the heat generated by the cal rod will vary with the square of the radial distance from it.
- You can parametrically study various cal rod set-ups using thermal software, or Excel, or simple hand calculations.
- I recently went through this for my project (GOES-R) to optimize cal rod spacing and setback to achieve a relatively even flux distribution on the radiators.
  - The GOES-R radiators are very large, but contain many heat pipes to spread the electronics heat (aka “isothermalize” the panels), so a perfectly even flux distribution isn’t critical.

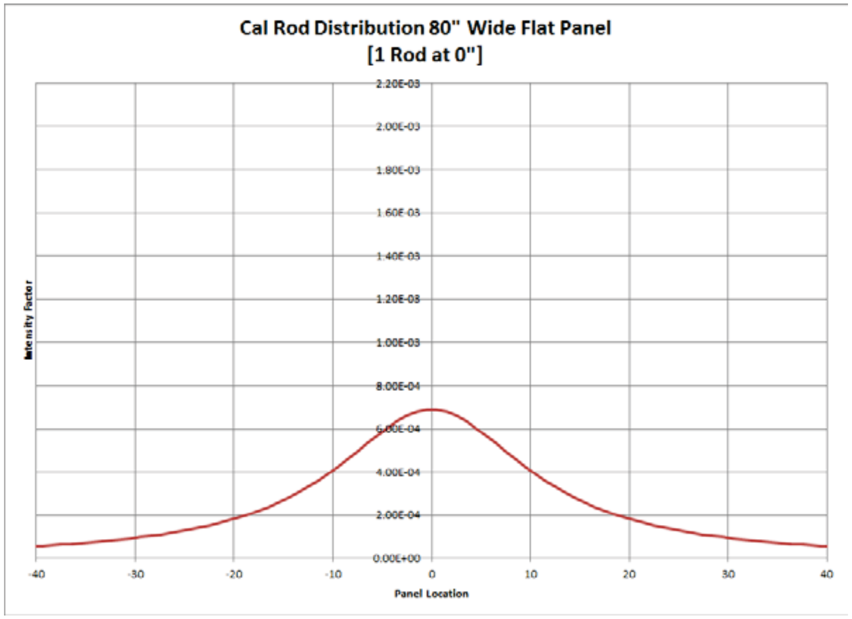
Single Cal Rod – Intensity vs Setback

- The data shows that as the cal rod – surface distance increases. the peak intensity goes down, reducing the variation (min-max) on the surface, resulting in a “smoother” distribution.
- So you can imagine that the effect of lining up multiple cal rods (at one of these setbacks shown on the plot) would be to add multiple peaks while increasing the overall intensity level on the panel.
- This variation in intensity is why you need ESDs to measure the sink temperature “average”. You do not want uncertainty in your sinks for model correlation.

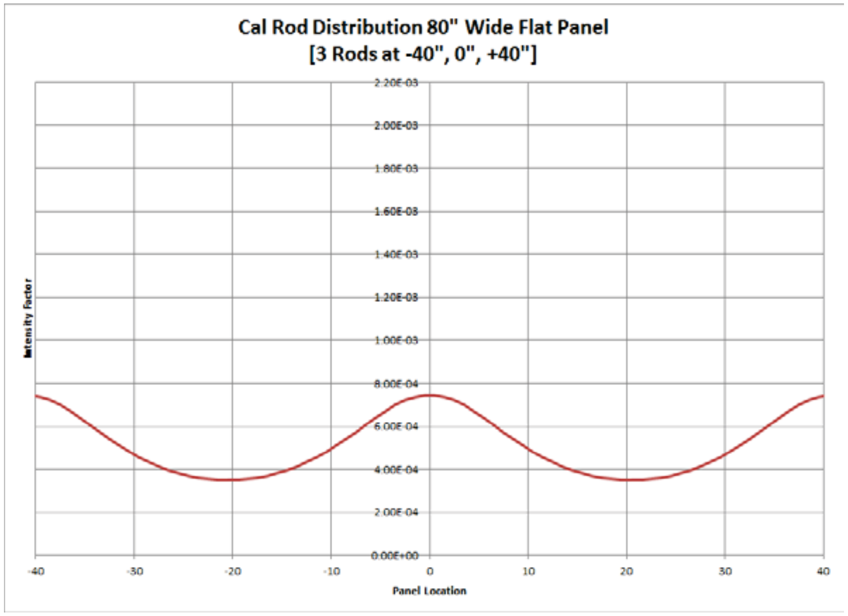


Effect of Multiple Cal Rods at Fixed Setback

- Assumed 80" wide panel
- Single cal rod set back 12" from panel

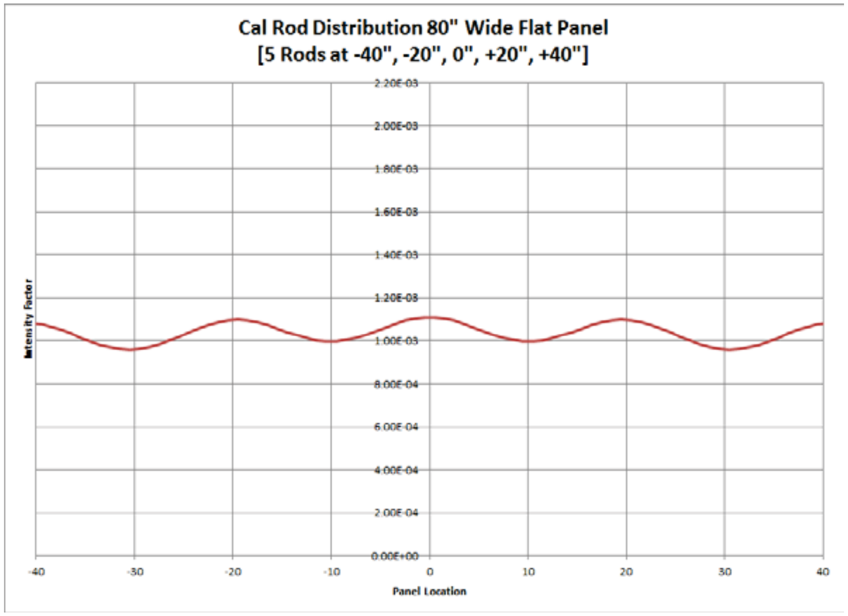


- Three cal rods set back 12" from panel; spaced 40" apart.

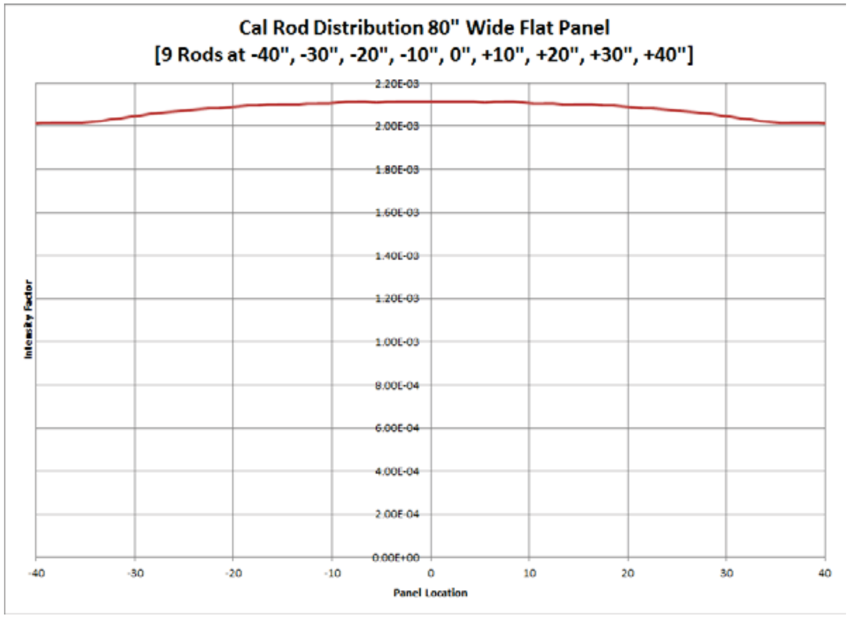


Multiple Cal Rods - continued

- Five cal rods set back 12” from panel; spaced 20” apart

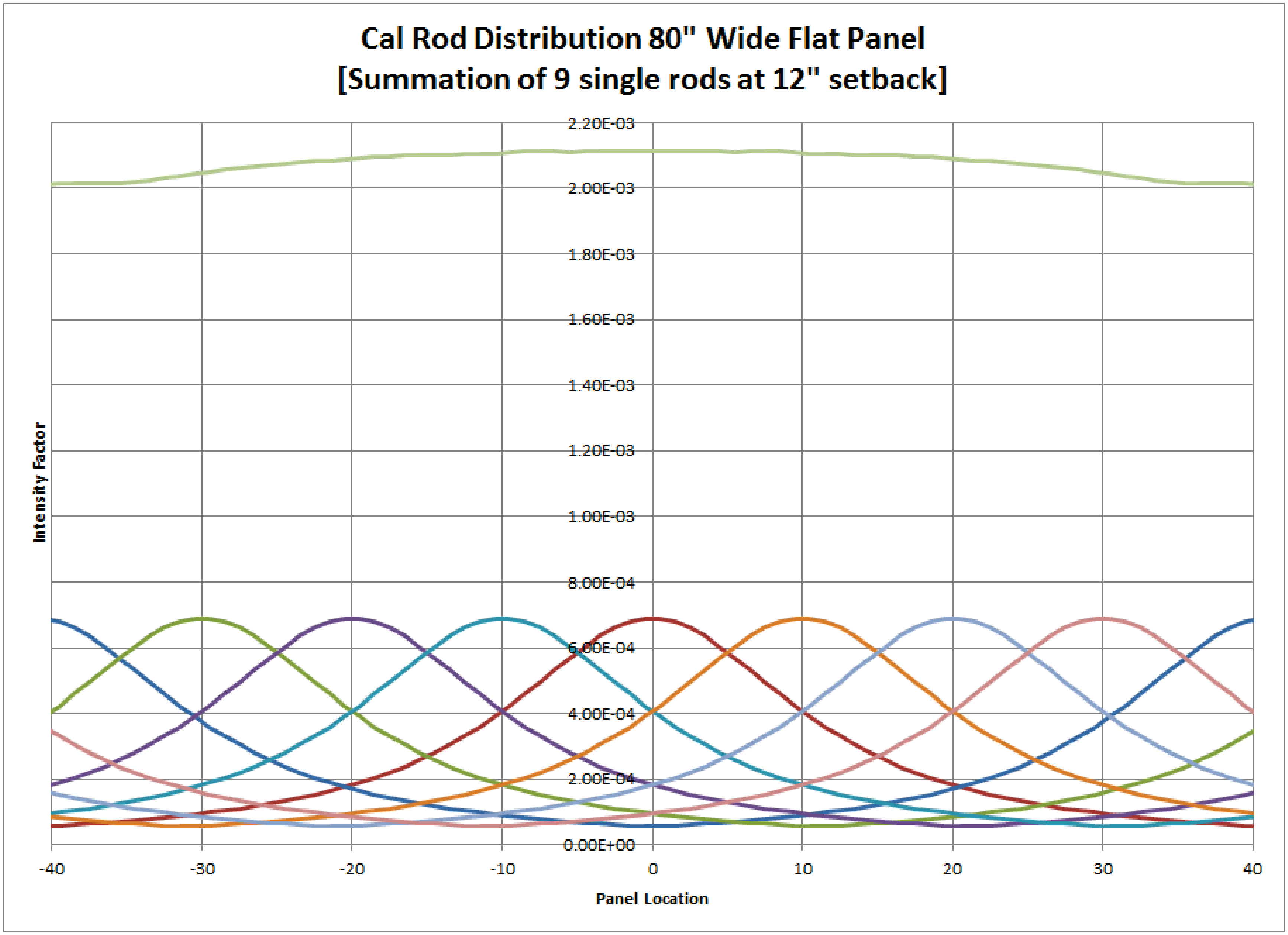


- Nine cal rods set back 21” from panel; spaced 10“ apart.



	I 9 rods	I 5 rods	I 3 rods	I 1 rod
Min:	2.01E-03	9.60E-04	3.52E-04	5.56E-05
Avg:	2.07E-03	1.04E-03	5.19E-04	2.59E-04
Max:	2.11E-03	1.11E-03	7.43E-04	6.88E-04
Min/Max variation:	5.0%	15.5%	111.4%	1136.9%

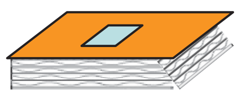
Nine Cal Rods – Sum of All Parts

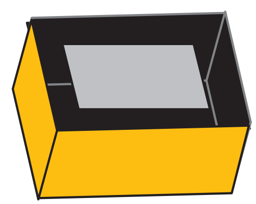


Equivalent Sink Detectors

- Still use an Equivalent Sink Detector, or "ESD" to measure sink temperature (flux)

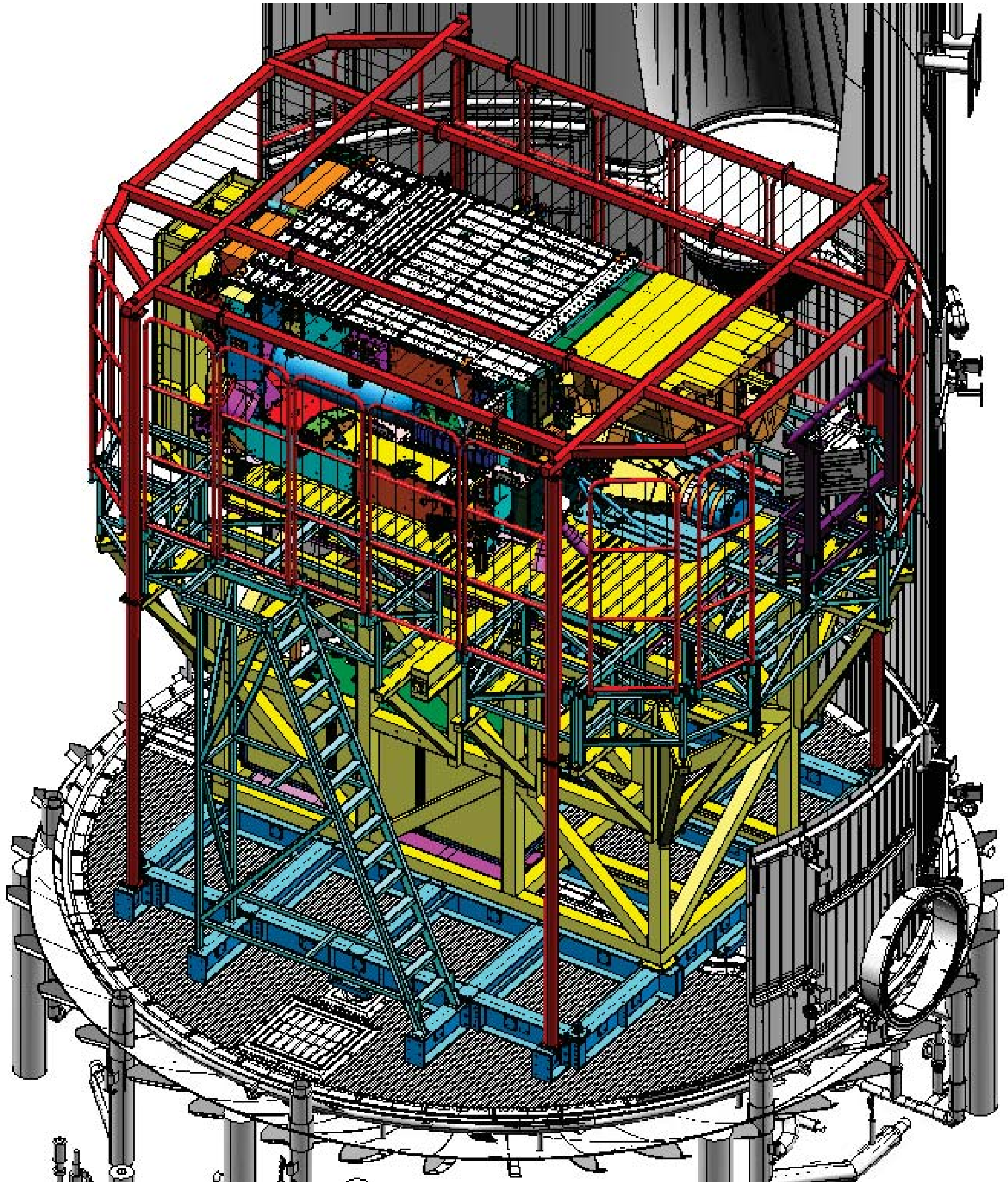
- Based on the "patch" approach to analytically determining sink temperatures. Various designs but some basics need to be followed:
  - Small piece of material - same as your test article surface you're setting the sink for.
  - TCs for data logging.
  - Must isolate from heating effects from test article.





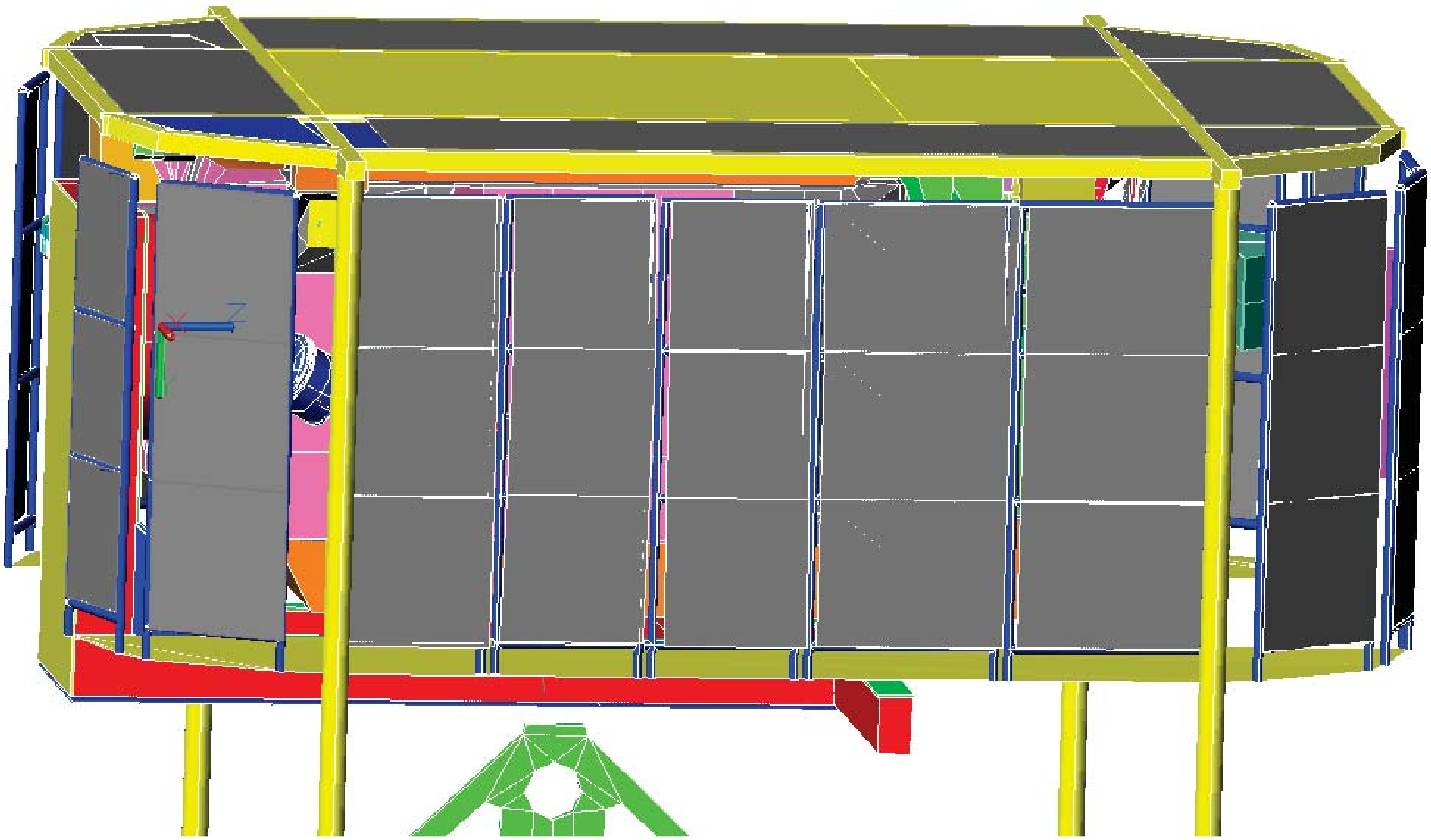
GOES-R SCTV configuration

- Cal rod "zones" around the -Y, +/-X, +/-Z sides of the SC.
  - +Y uses GN_2 temperature controlled coldplate
- Deployed solar array (yoke and instrument platform – no cell panels) uses heater plates to provide discrete environments to co-located instruments



Modeling the GOES-R Test - Example

- Cal rod zones modeled as black plates in SCTV thermal model, set at desired equivalent sink temperature.
- Mylar baffles separating zones are also modeled.



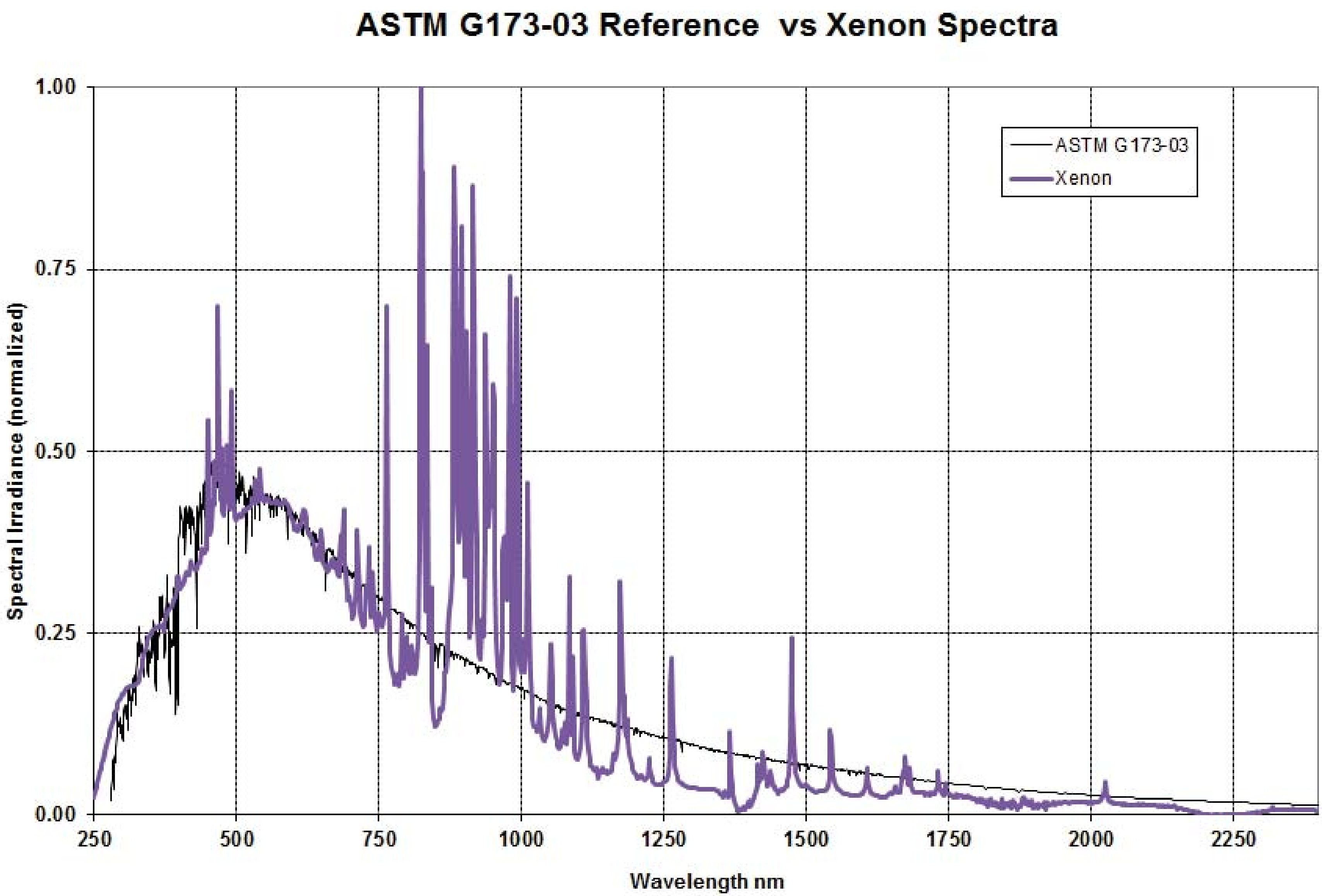
Solar Simulation

- Solar simulation is [arguably] the Cadillac of mission environment simulation, but:
  - Troublesome for IR simulation, so use only for missions away from planetary IR heating.

- Few test facilities available for solar simulation; especially at the spacecraft level.

- Xenon lamps typically used to simulate solar irradiance; closely matches solar spectrum, but:
  - Spectral content must be measured, analyzed and analytical properties adjusted.
  - Beam “quality” should be measured for planned intensities.

UV vs Xenon Spectra



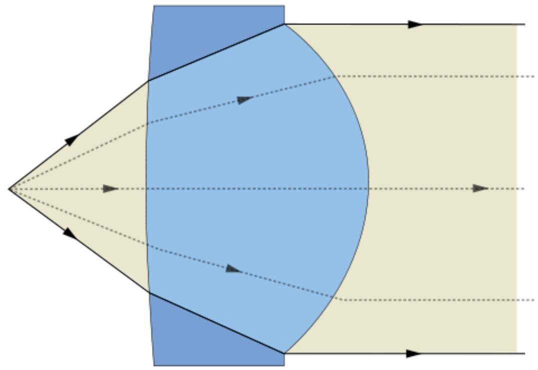
Spectral Energy Distribution

- Solar simulation is just that – not perfect but can be very close.
- Since α and I are f(λ), the differences in spectral energy distribution between UV and Xenon require re-calculating thermo-optical properties for correlation.

$$\boldsymbol{\alpha}_{\mathbf{EFF}} = \frac{\int \boldsymbol{i}(\lambda)\alpha(\lambda)\boldsymbol{d}(\lambda)}{\int \boldsymbol{i}(\lambda)\alpha(\lambda)}$$

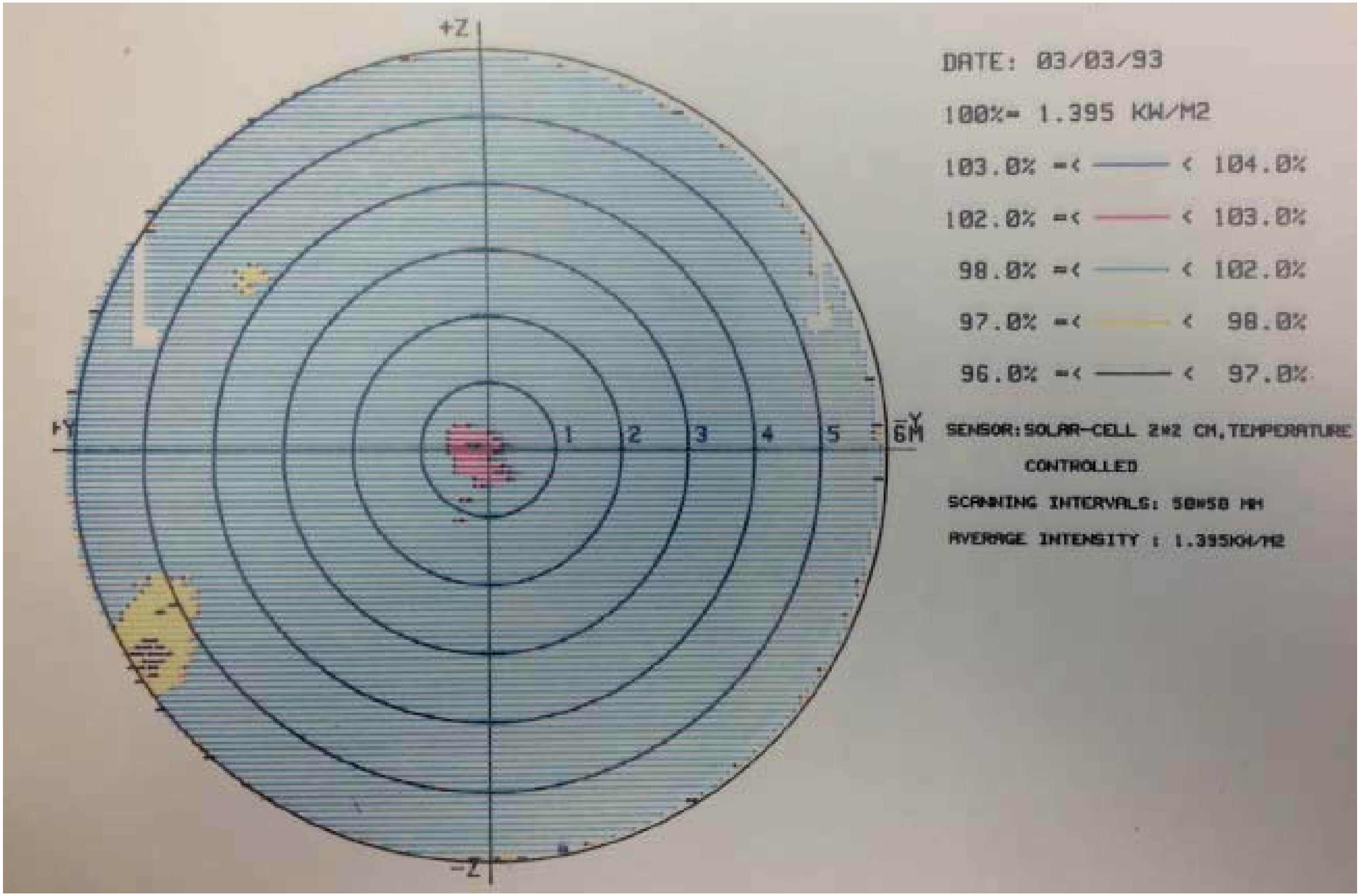
Beam Collimation (Quality)

- UV energy (light) from the sun flows radially outward - the UV intensity is proportional to the square of the distance from the sun, based on the surface area of an ever-growing sphere.
- For a sphere r=1 AU, the size of a spacecraft is infinitesimally small (dA) and for thermal purposes, the irradiance is considered perfectly collimated, i.e.- there is no angular difference within dA.
- Solar simulation beams cover small distances and the normal divergence from a UV source requires “collimation” to achieve a consistent irradiance across the beam field (width and depth). Mapping the beam intensity across, and through the depth of the field, is a key parameter to a solar sim test.



• Intensity	70 - 2600W/m²
• Collimation angle	+/- 1.9°
• Sun stability at 1 SC	+/- 0.5%
• In-plane uniformity at 1 SC	+/- 4%
• In-volume uniformity at 1 SC	+/- 6%

Beam Intensity Mapping



4.0 Test Set-up

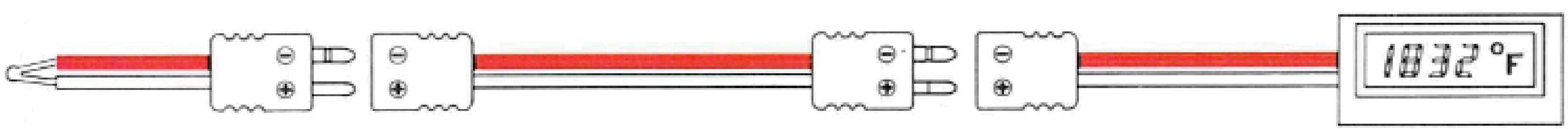
- 4.1 Mission Environments
- 4.2 Chambers/GSE
- 4.3 Temperature Sensors/Alarm Limits

Thermocouples (TCs)

- TCs are the most commonly used type of test temperature sensor due to simplicity, ease of use and their speed of response to changes in temperature, due mainly to their small size. The various types allow use over a wide temperature range (<-200°C to >2000°C).
- TCs are thermoelectric sensors that consist of two junctions of dissimilar metals, such as copper and constantan (Type T) that are welded together.

Thermocouple wire Letter Designator	T	J	E	K	N
Alloy Combination & Polarity	(+) Copper (-) Constantan	(+) Iron (magnetic) (-) Constantan	(+) Chromel™ (-) Constantan	(+) Chromel™ (-) Alumel™ (magnetic)	(+) Nicrosil (-) Nisil
Insulated Thermocouple wire Color Code **Note**: Some insulations cannot be color coded	BLUE (+) RED (-) BROWN	(magnetic) WHITE (+) RED (-) BROWN	PURPLE (+) RED (-) BROWN	YELLOW (+) RED (-) (magnetic) BROWN	ORANGE (+) RED (-) BROWN
Bare Wire Temperature Range **Note**: Smaller wire sizes have shorter T/C life at higher temperatures	660°F (350°C) -330°F (-200°C)	1400°F (750°C) 32°F (0°C)	1600°F (900°C) 32°F (0°C)	2300°F (1250°C) 32°F (0°C)	2300°F (1250°C) 32°F (0°C)

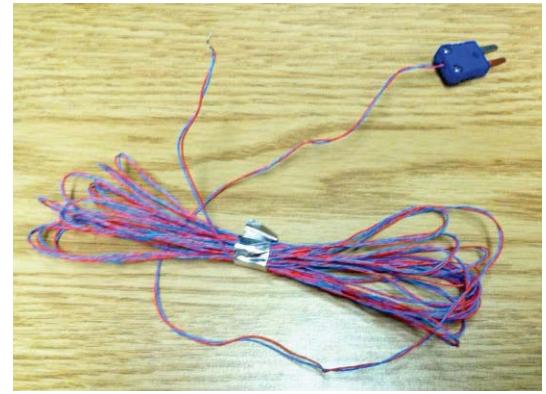
- One junction is kept at a constant temperature (cold reference), while the other is mounted where you want to know the temperature (hot junction).

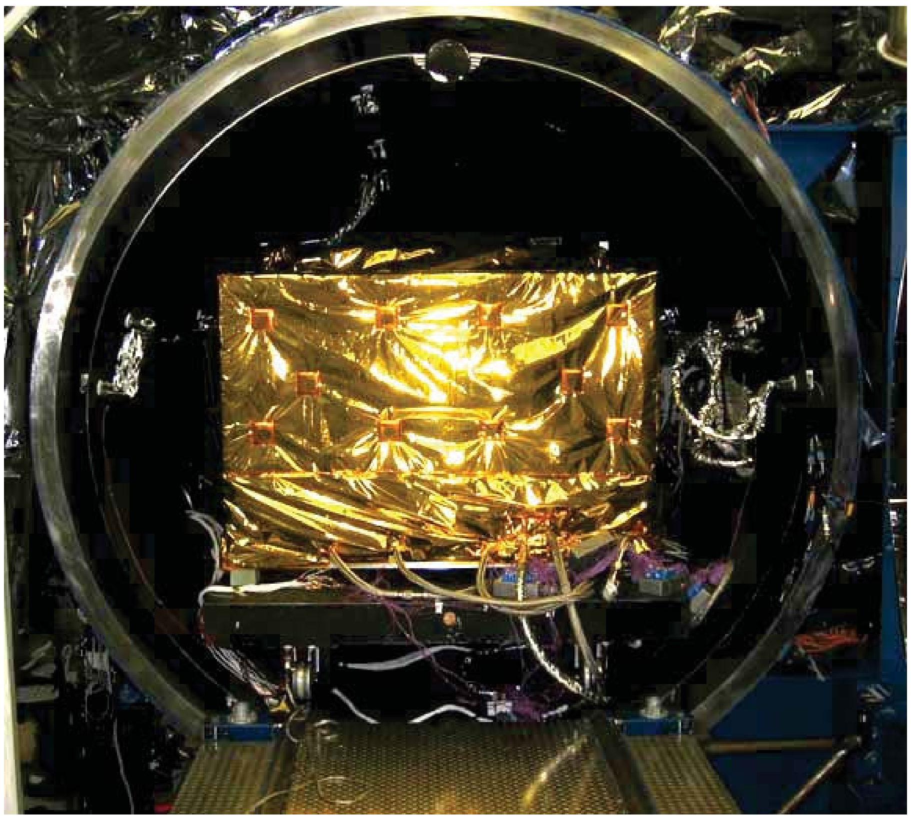


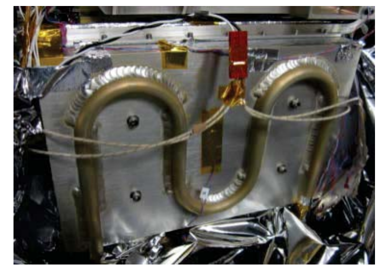
Making a Thermocouple

+

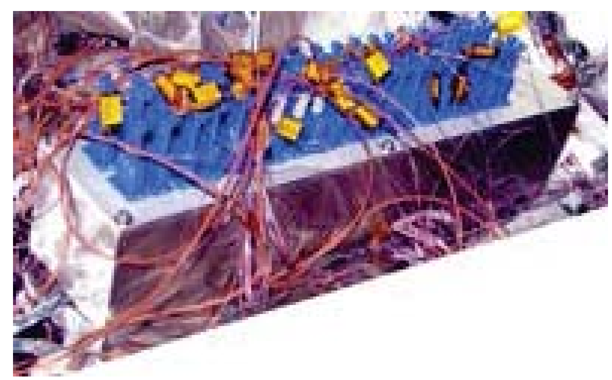
=





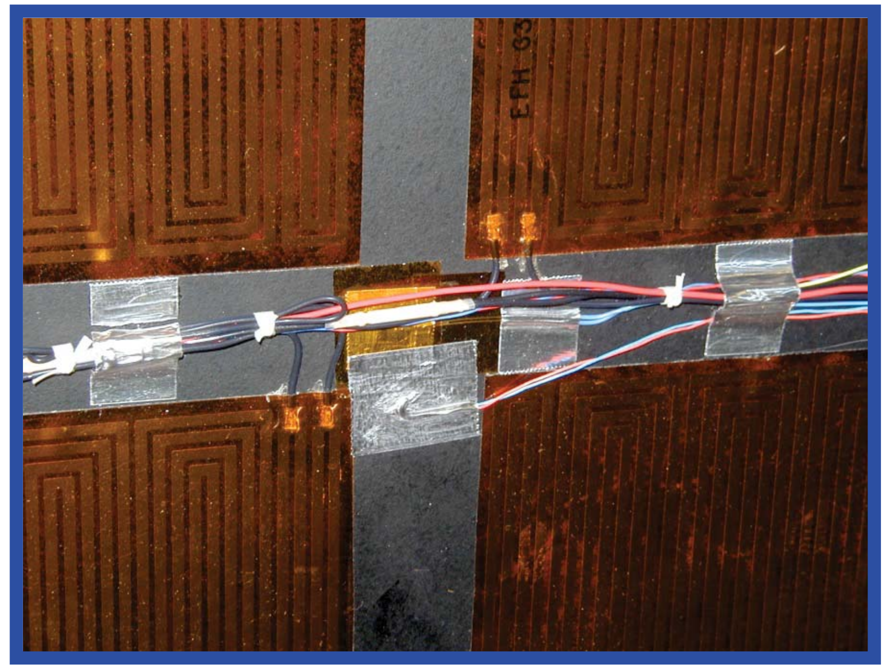


X 100's



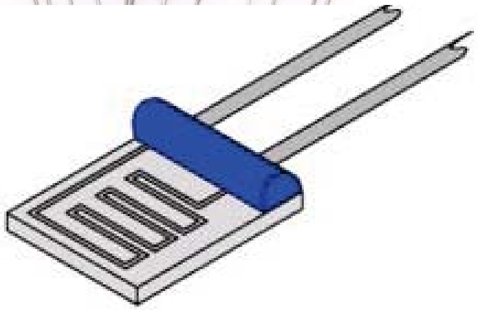
Installing Thermocouples

- The vast majority of thermocouples are mounted with adhesive-backed aluminum tape. Form the end of the thermocouple wire pair into a "U" shape to hold the thermocouple in place in case the wire is accidentally pulled.
- Connect to facility data system and verify all TCs read close to ambient.
- Touch test.



Resistive Temperature Devices

- Precision temperature sensors made from high-purity conducting metals such as platinum, copper or nickel wound into a coil and whose electrical resistance changes as a function of temperature, similar to that of the thermistor.
    - Also available are thin-film RTD's. These devices have a thin film of platinum paste is deposited onto a white ceramic substrate
- Thermistors
    - THERM-ally sensitive res-ISTOR: special type of resistor which changes its physical resistance when exposed to changes in temperature.
    - Generally made from ceramic materials such as oxides of nickel, manganese or cobalt coated in glass which makes them easily damaged. Main advantages: speed of response to any changes in temperature, accuracy and repeatability.
        - Negative Temperature Coefficient of resistance or (NTC), that is their resistance value goes DOWN with an increase in the temperature,
        - Positive Temperature Coefficient, (PTC) resistance value goes UP with an increase in temperature.
- Silicon Diode: The silicon diode sensor is a device that has been developed specifically for the cryogenic temperature range. Essentially, they are linear devices where the conductivity of the diode increases linearly in the low cryogenic regions.
- Platinum Resistance Thermomoeter (PRT): stable unreactive metal which can be drawn down to fine wires but is not too soft. Using very pure wires, thermometers can be made with closely similar resistance characteristics and achieve good reproducibility in use.
- Cernox™ thin film resistance cryogenic temperature sensors
    - Temperature range of 100 mK to 420 K (model dependent)
    - High sensitivity at low temperatures and good sensitivity over a broad range



1-Wire Sensor

- Digital thermometer used by MMS for GSE temperature sensing.
  - $-55°C < T_{OPER} < +125°C$; +/-0.5° accuracy $-55°C < T_{OPER} < +85°C$
  - Sensors actually have three wires (Data, Power and Ground)
  - Install same as thermostats & thermistors (Stycast, Ecoobond, etc)
- Pros
  - Each sensor has a unique 64-bit address allowing multiple sensors to be wired in series – similar to Christmas Tree lights
  - Compared to a typical thermocouple that uses two wires, the 1-Wire sensors can save GSE mass and can be read using a USB interface and laptop computer.
- Cons
  - If 1-wire bus shorts to ground you lose the entire string

MMS used six 1-wire buses w/64 sensors each. So for ~400 sensors, only had 18 wires going to the chamber connector. TCs would have required ~800 wires.

Data Systems

- Institutional heritage usually drives the TC data system set up and capability.
- Mission unique telemetry parameters drive the TLM display.
- Thermal test telemetry should utilize ALL temperature, heater, and current telemetry to the maximum extent possible.
- Set up display pages before test begins – although they will undoubtedly be modified as the test progresses, Some suggestions:
  – Create virtual channels for gradients, dT/dt, etc
  – Labview displays using schematics with telemetry displayed, i.e. – propulsion systems, two-phase thermal systems,
  – Stability pages to monitor required dT/dt for all sensors

Stability Monitoring

- Use virtual channels to calculate dT/dt, and setup display pages to follow.
- Example: MMS created pages to show dT/dt for 4 hour windows to track meeting their <0.1°C/hour (for 4 hours) requirement.

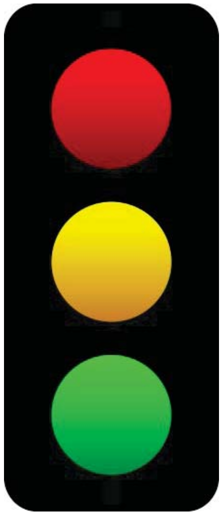
TCS_1WIRE_BALANCE:

GMT: 13-314-15:42:39.00
S/C: 13-314-15:42:34.12
P5DCSCNT: 3180
TCS_1WIRE_BALANCE
Hot Cold Balance
SC ID: MMS2ok
SC SIDE: A
CLOSE
SNAP
Hot Cold Bal
Cold Surv

CONTROL ZONES	Sensor Location	Current temp	Stblty Req deg C/1 hr	1st hr avg slope	2nd hr avg slope	3rd hr avg slope	4th hr avg slope	4 hr crit met
Spacecraft Deck								
Bay # 1 (Nav + USO)	SC_112 SC Deck Bay 1 external facesheet (next to NAV radiator)	+18.31ok	0.190	-0.125	-0.063	-0.125	-0.063	
	SC_004 SC Deck to Navigator I/F (On Navigator)	+20.56ok		-0.063	-0.125	-0.063	-0.125	
	SC_098 USO 1 foot	+15.69ok		-0.063	-0.125	-0.063	-0.063	
Bay # 2 (Battery)	SC_113 SC Deck Bay 2 external facesheet center	+11.94ok	0.050	-0.125	-0.125	-0.125	0.000	
	SC_019 SC Deck to Sun Sensor I/F (On Sun Sensor)	+11.00ok		-0.125	-0.063	-0.063	-0.125	
	SC_123 Battery I/F (On Battery)	+17.31ok		-0.188	-0.250	-0.125	-0.188	
Bay # 3 (F/D)	SC_114 SC Deck Bay 3 external facesheet center	+10.12ok	0.190	-0.063	-0.125	-0.063	0.000	
	SC_027 SC Deck to Fill/Drain panel I/F (On F/D Panel 1)	-10.38ok		0.063	0.000	-0.188	0.188	
	SC_021 SC Deck skin Connector Panel	+10.81ok		-0.125	-0.063	-0.063	-0.125	
Bay # 4 (Comm)	SC_089 SC Deck Bay 4 external facesheet (next to TRANS radiato	+12.25ok	0.190	-0.063	-0.063	-0.063	-0.063	
	SC_036 SC Deck to Transmitter B I/F (On Transmitter)	+19.06ok		-0.063	-0.125	-0.063	0.000	
	SC_038 SC Deck to Transmitter A I/F (On Transmitter)	+17.69ok		-0.063	-0.063	-0.063	-0.125	
	SC_095 Bay 4 CHU 2	-22.75ok		-0.063	-0.063	-0.063	-0.063	
Bay # 5 (C&DH)	SC_090 SC Deck Bay 5 external facesheet (next to C&DH Radiator	+15.81ok	0.140	-0.125	-0.063	-0.063	-0.063	
	SC_045 SC Deck to C&DH I/F (On C&DH)	+17.19ok		-0.125	-0.063	-0.125	0.063	
Bay # 6 (Star Sensor)	SC_091 SC Deck Bay 6 external facesheet center	+05.19ok	0.190	-0.063	-0.125	-0.063	0.000	
	SC_058 SC Deck to DPU I/F (On DPU)	+16.06ok		-0.125	-0.063	-0.063	-0.063	
	SC_068 Bay 6 CHU Bench	-27.81ok		-0.063	-0.063	-0.063	-0.063	
Bay # 7 (MIS)	SC_092 SC Deck Bay 7 external facesheet center	+11.75ok	0.190	-0.063	-0.063	-0.063	-0.063	
	SC_065 SC Deck Skin Connector Panel	+11.81ok		-0.063	-0.063	-0.063	-0.125	
Bay # 8 (PSEES)	SC_093 SC Deck Bay 8 external facesheet (next to PSEES Radiato	+12.56ok	0.190	-0.063	-0.125	-0.063	-0.063	
	SC_030 SC Deck to PSEES I/F (On PSEES)	+15.31ok		-0.125	-0.063	-0.063	-0.063	
Instrument Deck								
Bay # 1 (+X DIS/DES)	IS_127 External IS Deck Surface Bay 1	+16.50ok	0.125	-0.063	-0.125	-0.063	-0.063	
	IS_013 DIS Chassis	+20.12ok		-0.063	-0.125	-0.063	-0.063	
	IS_008 DES Thermostats	+15.31ok		-0.063	-0.063	-0.063	-0.063	
Bay # 2 (CIDP)	IS_128 External IS Deck Surface Bay 2	-15.75ok	0.125	-0.063	-0.063	-0.063	-0.063	
	IS_027 INS Deck to CIDP I/F (On CIDP)	-18.56ok		-0.125	-0.063	-0.125	-0.063	
	IS_031 INS Deck to SDP I/F (On Bracket)	-14.69ok		-0.063	-0.125	-0.063	-0.125	
	IS_024 INS Deck to ASPOC Bracket (On Bracket)	-15.75ok		-0.125	-0.063	-0.063	-0.125	
Bay # 3 (+Y DIS/DES)	IS_129 External IS Deck Surface Bay 3	+14.75ok	0.125	-0.063	-0.125	-0.063	-0.063	
	IS_037 DIS Chassis	+19.75ok		0.000	-0.063	-0.063	-0.063	
	IS_042 DES Thermostats	+14.31ok		0.000	-0.063	-0.063	-0.063	
Bay # 4 (IDPU/EDI) (EIS/SDP)	IS_130 External IS Deck Surface Bay 4	+10.31ok	0.110	0.000	-0.063	-0.063	-0.125	
	IS_056 INS Deck to IDPU I/F (On IDPU)	+18.38ok		-0.063	-0.063	-0.125	-0.063	
	IS_052 INS Deck to EDI-GDU I/F (On EDI/GDU)	+12.50ok		-0.063	-0.063	-0.063	-0.063	
	IS_054 INS Deck to EIS I/F (On EIS)	+20.88ok		-0.063	-0.063	-0.063	-0.063	
	IS_058 INS Deck to SDP I/F (On Bracket)	+15.50ok		-0.063	-0.063	-0.125	0.000	
Bay # 5 (-X DIS/DES)	IS_131 External IS Deck Surface Bay 5	+15.44ok	0.125	-0.063	-0.125	-0.063	-0.063	
	IS_068 DIS Chassis	+19.38ok		-0.063	-0.063	0.000	-0.188	
	IS_072 DES Thermostats	+14.50ok		-0.063	-0.063	-0.063	0.000	
Bay # 6 (SDP/HPCA) (ASPOC)	IS_132 External IS Deck Surface Bay 6	+09.56ok	0.125	-0.063	-0.063	-0.063	-0.063	
	IS_095 INS Deck to SDP I/F (On Bracket)	+13.25ok		-0.063	-0.063	-0.063	-0.063	
	IS_093 INS Deck to HPCA I/F (On HPCA)	+12.75ok		-0.063	0.000	-0.063	-0.063	
	IS_091 INS Deck to ASPOC I/F (On Bracket)	+13.62ok		-0.063	-0.063	-0.063	-0.063	
Bay # 7 (CEB) (-Y DIS/DES)	IS_133 External IS Deck Surface Bay 7	+17.81ok	0.125	-0.125	0.000	-0.063	-0.063	
	IS_111 INS Deck to CEB Interface (On CEB)	+19.56ok		-0.063	-0.063	-0.063	-0.063	
	IS_100 DIS Chassis	+19.00ok		-0.063	-0.063	-0.063	0.000	
	IS_105 DES 4 Thermostats	+15.88ok		-0.063	0.000	-0.063	0.000	
Bay # 8 (SDP, EDI)	IS_134 External IS Deck Surface Bay 8	+11.00ok	0.050	-0.125	0.000	-0.063	-0.063	
	IS_121 INS Deck to SDP 4 I/F (On Bracket)	-15.81ok		-0.063	-0.063	-0.063	-0.063	
	IS_116 INS Deck to EDI-GDU I/F (On EDI-GDU Baseplate, Internal	-14.88ok		-0.063	-0.063	-0.063	-0.063	
Thrust Tube, ODS & Gold Plated Rings								
+Z ODS and Rings	PRP_008 Bulkhead to Top ODS Interface (On ODS)	+05.75ok	0.500	-0.125	0.000	-0.125	0.000	
	PRP_015 Top ODS Ring Interface (On Top ODS)	+07.62ok		-0.063	-0.063	-0.063	-0.063	
	PRP_016 Top ODS to Ring Interface (On Top Ring)	+20.56ok		-0.125	-0.063	-0.063	0.000	
-Z ODS and Rings	PRP_007 Bulkhead to Bottom ODS Interface (On ODS)	+00.56ok	0.500	-0.063	-0.125	-0.063	-0.125	
	PRP_049 Bottom ODS To Ring Interface (On Bottom ODS)	+01.81ok		0.000	-0.125	-0.125	-0.188	
	PRP_050 Bottom ODS To Ring Interface (On Bottom Ring)	+13.50ok		-0.188	0.063	-0.125	-0.125	

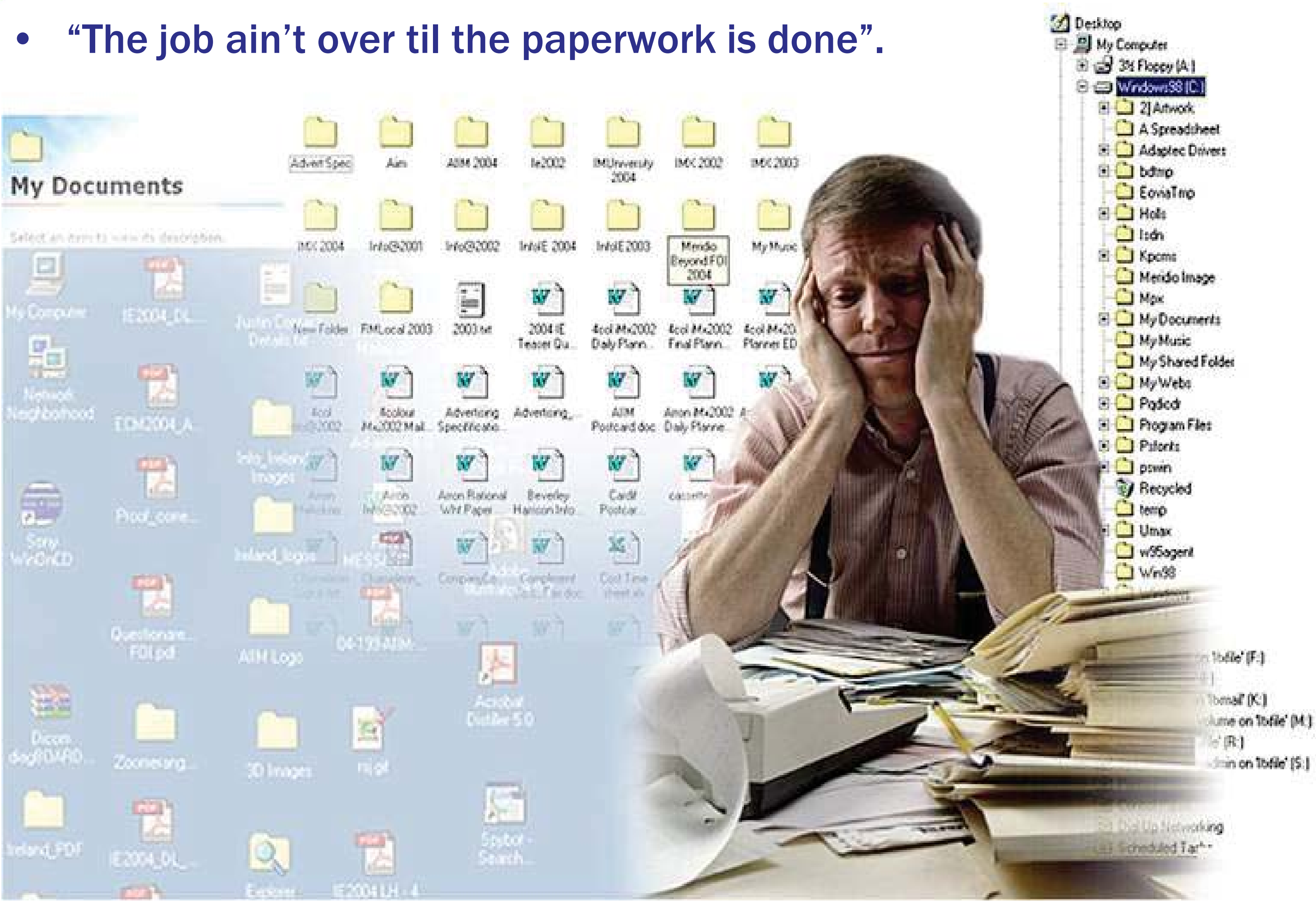
Alarm Limits

- Most companies/institutions have their own idea on where to set YEL/RED limits.
- The key is to understand what happens if a limits is reached/exceeded; driven by hardware safety and mission assurance.
- GSFC practice usually sets these limits as:
  - Yellow: outside of allowable operational range
  - Red: outside of hardware test range(i.e. protoflight, etc)
- Tolerances ?



RED = Stop. You shouldn't be here.
Paperwork is generated
YEL = use caution. This is not a typical range.
No paperwork generated.
Green = good.

- “The job ain’t over til the paperwork is done”.



Thermal Test Documentation

- GSFC-STD-1001 “Criteria for Flight Project Critical Milestones” defines requirements for critical reviews.
- Documentation for thermal verification testing begins at CDR:
  - Test plans complete
  - Environmental verification flow from component to system level.
  - Test facilities have been defined. Facilities are available and, if needed, utilization agreements are complete
- At PER, “.... comprehensive environmental test sequence at appropriate exposure levels is planned that will complete all remaining required verification activities.”

Documentation Requirements

- The Goddard Space Flight Center Thermal Branch requires analysis documentation (report / charts):
  - Pre-Test: complete set of test predictions (temperatures & heater power) for all thermal balance plateaus and hot/cold cycles, plus transient assessment to verify transition times/schedule.
  - Post-Test:
    - Quick-look memo (within 2 weeks of balance completion) documenting thermal balance temperatures compared to pre-test predictions with NO model correlation.
    - Post-Correlation thermal model review
    - Final thermal test report
      - Thermal balance model correlation
      - Summary of cycle plateau temperatures achieved and margin analysis to MAT and predicts
      - Mission predictions
- We have some preferred products/formats, which I will try to go thru with some examples.

Pre-Test Analysis

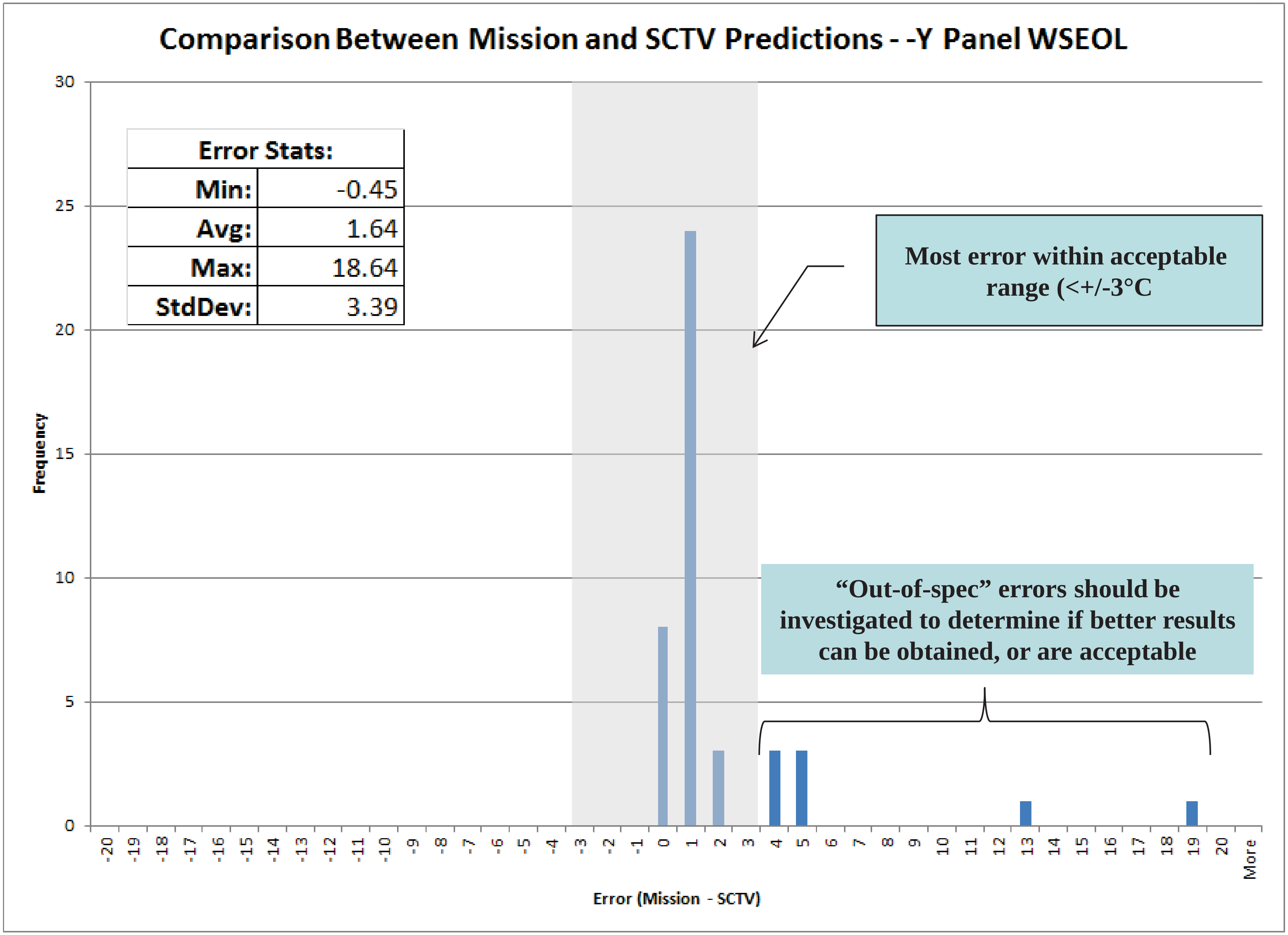
- Present at PER
- Document in engineering memos, reports, etc
  - Target design, sizing, etc
- Analysis must include:
  - all balance plateaus: present in "rainbow" format, with "errors" between simulated and corresponding mission cases tabulated and in histograms.
  - hot & cold cycle plateaus: present in "rainbow" format, with "errors" between predict and protoflight temperatures tabulated and in histograms.
    - CPT/LPT operations may differ from planned mission operations, but this is usually the dissipation configuration we use.
  - Transients: to assess durations, and to ID possible contamination issues

Example - Balance vs Mission

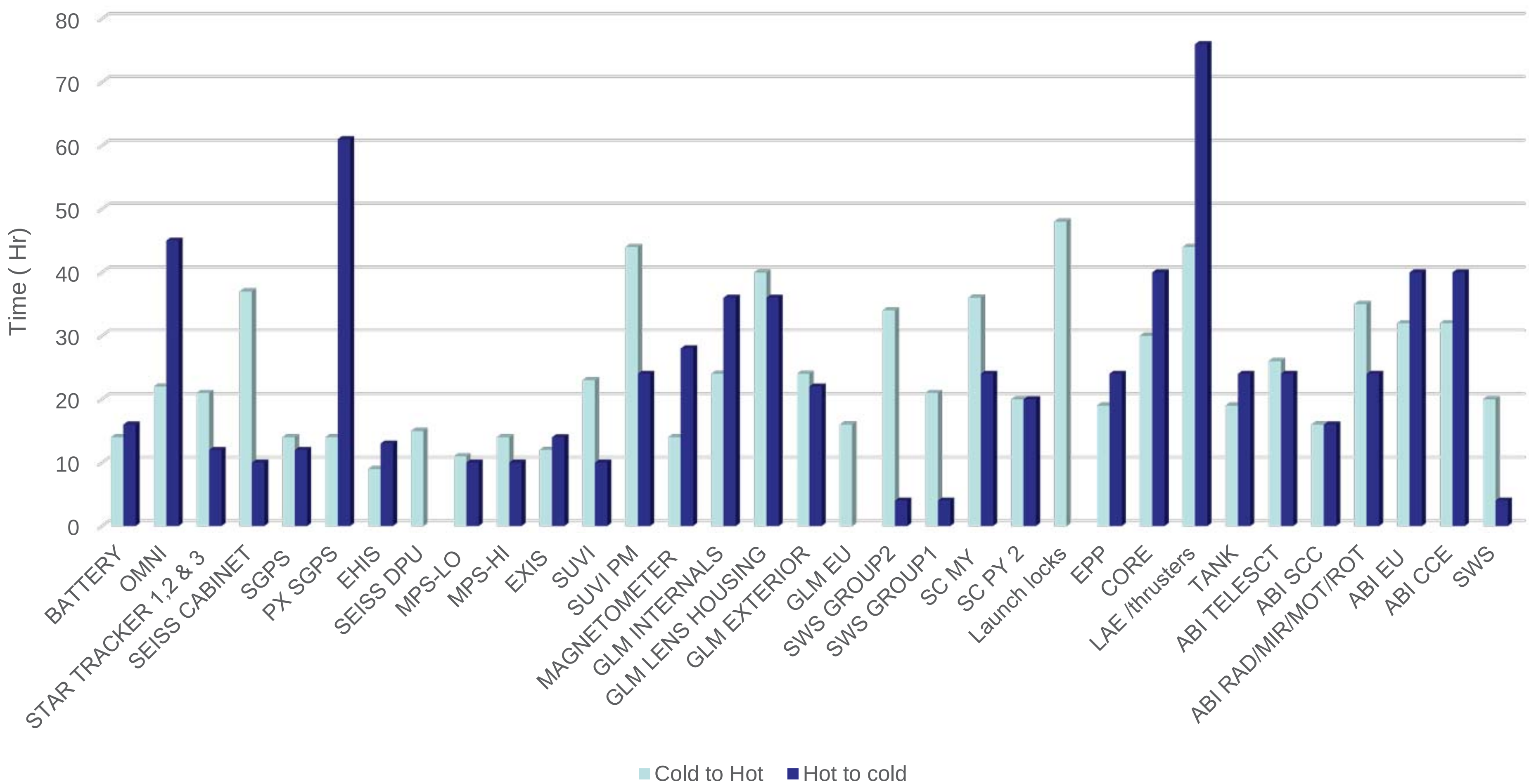
- Single Excel file containing all reported items:
  - Unit I/F's
  - TLM sensors
  - Gradients
  - Heater Power
- Along with all analysis results, TLM mnemonics, corresponding node numbers, circuit ref des, etc.
- Summary tables are important for documenting all detail, but not very user friendly for quick-look understanding.

	Protoflight Temperature Range	Acceptance Temperature Range	Mission Allowable Temperature Range	Allowable Raw Prediction	Raw Predictions (°C)									
					AEBOL		SSEOL		WSEOL					
Delta = Mission - SCTV					Tmin	Tmax	Tmin	Tmax	Tmin	Tmax				
Minus Y (North) Components														
Instrument Electronics														
ABI CCE 1	-10				-1	0			0	1				50
ABI CCE 2	-10				-2	0			0	1				50
ABI EU	-10				-2	0			0	1				50
GLM EU	-10				-3	0			-1	0				50
SEISS DPU	-30				14	25			13	19				50
Payload Components														
X SSPA 1	-29				-2	0			-1	1				66
X SSPA 2	-29				-2	0			0	1				66
RDM 1	-29				-2	0			0	1				66
RDM 2	-29				-1	0			0	1				66
XOFA 1	-29				-2	0			0	1				66
XOFA 2	-29				-2	0			0	1				66
Bus Components														
GPS LNA	-29				-1	8			7	12				66
GPS Receiver	-29				-2	0			-1	1				66
GPS Receiver	-29				-2	0			-1	1				66
FBA 1	-29				-2	0			-1	1				66
FBA 2	-29				-2	0			0	1				66
RIU 2	-29				-3	0			-2	0				66
RIU 1	-29				-3	0			-2	0				66
RWA 6	-23				-2	3			-1	3				71
RWA 5	-23				-2	3			0	4				71
RWA 4	-23				-2	3			0	4				71
RWA 3	-23				-3	3			0	4				71
RWA 2	-23				-3	3			0	5				71
RWA 1	-23				-3	4			0	5				71
SPRU SAS 1	-29				-3	0			-2	0				66
SPRU SAS 2	-29				-3	0			-2	0				66
SPRU BCD 1	-29				-3	3			-2	0				66
SPRU BCD 2	-29				-3	3			-2	0				66
SPRU BCD 3	-29				-3	3			-2	0				66
SPRU CDA	-29				-3	0			-2	0				66
SPRU LPM 1	-29				-3	0			-2	0				66
SPRU LPM 2	-29				-3	0			-2	0				66
SPRU LCM	-29				-3	0			-2	0				66
SPRU EPDM 1	-29				-3	0			-2	0				66
SPRU EPDM 2	-29				-3	0			-2	0				66
SPRU EPDM 3	-29				-3	0			-2	0				66
OBC	-29				-2	0			-1	1				66
CTP	-29				-2	0			-1	1				66
CDUA	-29				-3	0			-1	1				66
SBT 1	-29				-2	0			-1	1				66
SBT 2	-29				-2	0			-1	1				66
CDAST 1	-29				-2	0			-1	1				60
CDAST 2	-29				-3	0			-1	1				60

Example - Balance vs Mission (continued)



Example - SC TVAC Transient Time Estimate



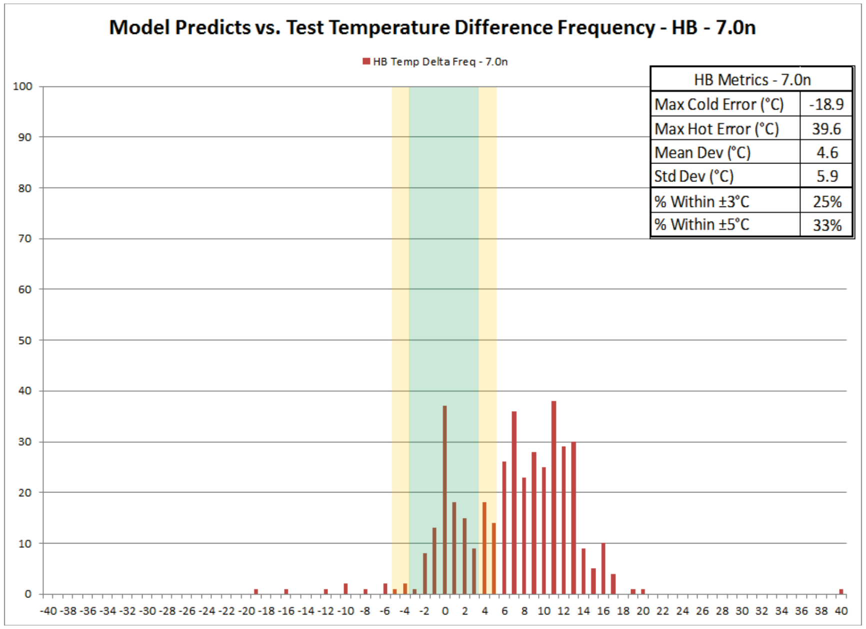
Post-Test Analysis

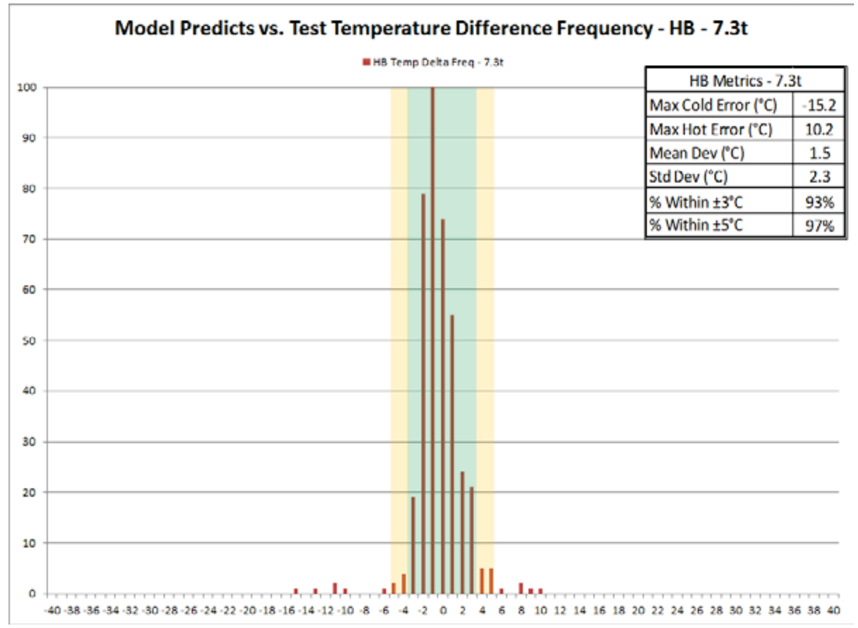
- "Quick-Look" report:
  - Release within 2 weeks of the completion of thermal balance testing. Document "Model – Data" errors; this is the starting point for the correlation effort.
  - Tabulate data in rainbow format with histograms. Include summary timeline for test.
  - Include "as measured" power – if available within the time constraints – this will be the basis for correlation.
  - Compare transients.
- Thermal Model Correlation report (by PSR) must include:
  - after correlation is completed for all balance plateaus; present in "rainbow" format, with "errors" between simulated and corresponding mission cases tabulated and in histograms (temperatures & heater powers).
  - Summary table of all changes made to the model, with their effect on statistical results; include statistics/trend for initial, final and "significant" changes.
  - Hot & cold cycle plateaus: present in "rainbow" format, with "errors" between predicted and actual protoflight temperatures tabulated and in histograms.
- Final mission predictions (by PSR):
  - Use correlated model for all mission cases. Document changes made as a result of the testing, if applicable.

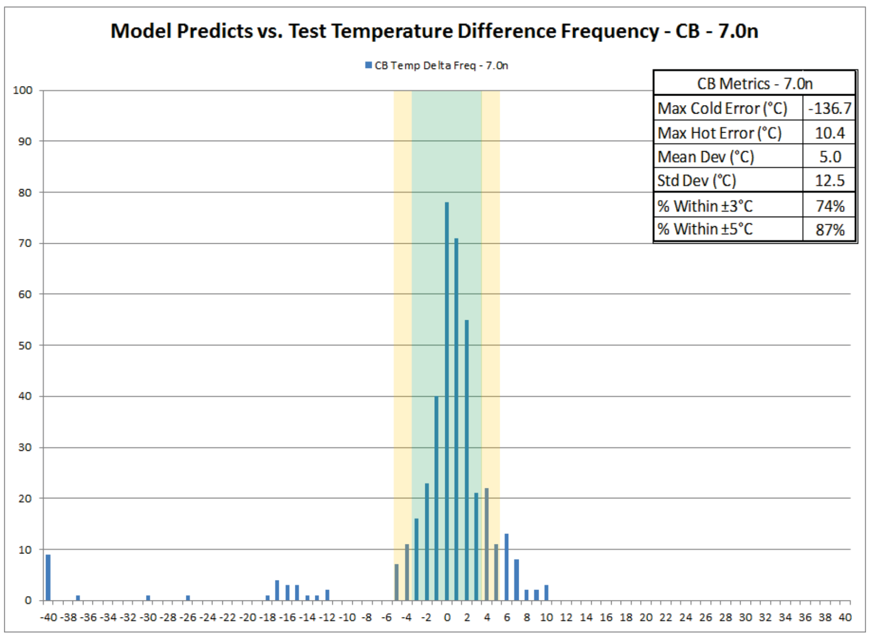
Model Correlation Review

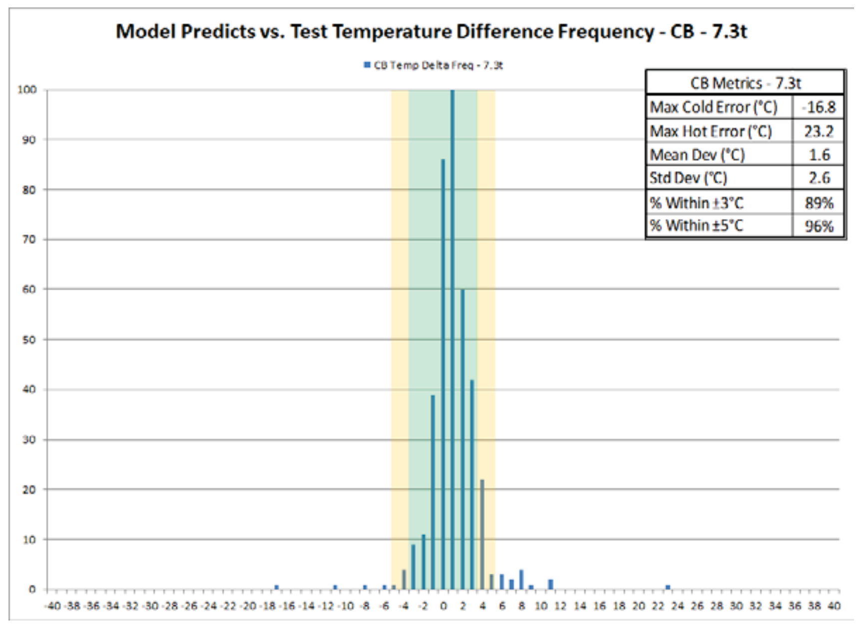
- Held when thermal model correlation is completed, or very close to it.
  - Use grey beards, other analysts, and independents
- Correlation statistical requirements are:
  - ΔT (avg): +/- 1.0 °C mean deviation
  - σ: 2.5 °C standard deviation
  - Calculate: and show Min ΔT and Max ΔT
    - All errors > 5 °C must be assessed as to why that is OK.
  - Calculate and show %error <3 °C and %error < 5 °C
  - Show transient comparisons
- Present all changes made to the model and the statistical analysis of the effect of each change on the error. Tabulate "the statistics" for the "non-significant" changes, tabulate and histograms for the "significant" changes.
- Identify changes to the flight design, if needed.

Example – Correlation Results (Initial & Final)









Thermal Balance Test Report

- This is basically a report summary of the model correlation peer review charts and data package.
  - Usually part of a CDRL requirement for Pre-Ship Review, along with the final models.
- Include overview of the test and major/significant finds/events/issues/etc.
- You could include your final mission predicts here, although a separate document (CDRL?) is usually required.
- Please use a technical report format, and not a PowerPoint format !!

Mission Correlation

- Usually not done, unless issues are seen in early mission.
- Difficult to do:
  - establishing exact environment that is steady enough to correlate, or
  - to do a transient correlation.
- While there are no “requirements” for the correlation, if telemetry is significantly off from the final predicts, it is still necessary to understand why. Usually:
  - Dissipation differences, environments
  - Property degradation
- Again, present all changes made to the model and the statistical analysis of the effect of each change on the error. Tabulate “the statistics” for the “non-significant” changes, tabulate and histograms for the “significant” changes.

Sources / References

- Fundamental information on thermal vacuum testing presented herein has been extracted from several sources, all of which are available in the public domain.
- References/Sources:
  - GSFC-STD-7000A "General Environmental Verification Standard (GEVS), For GSFC Flight Programs and Projects", April 22, 2013
  - MIL-STD-1540D "Product Verification Requirements for Launch, Upper Stage, and Space Vehicles", January 15, 1999
  - Cullimore & Ring [*www.crtech.com]*
  - "Spacecraft Thermal Control Handbook – Vols 1&2. Fundamental Technologies", Aerospace Corp, D. Gilmore, (Editor)
  - Space Mission Analysis and Design, Wertz & Larson
  - Various Aerospace Corp. papers, etc on Test Effectiveness
  - NASA Technical Reports Server, http://ntrs.nasa.gov

5.0 QUESTIONS ?