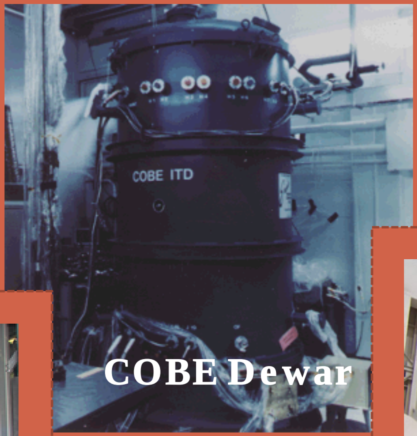
System Engineering Considerations for Planning Instrument/Observatory Level Thermal Vacuum Tests



SYSTEMS ENGINEERING SEMINAR

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JULY 10TH

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- Overview
- Test Levels and Basic Requirements
- Early Planning
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- Detailed Planning
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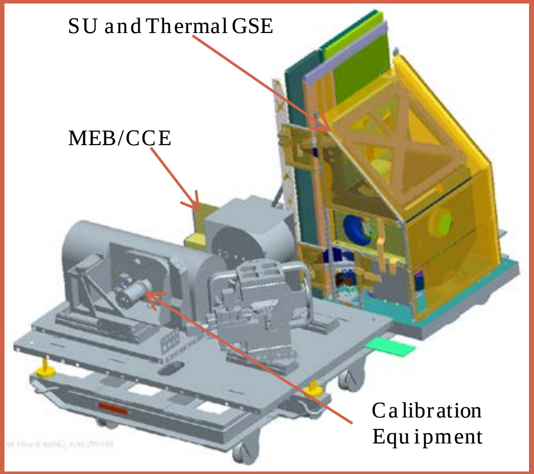
  - Emergency Planning
  - Documentation

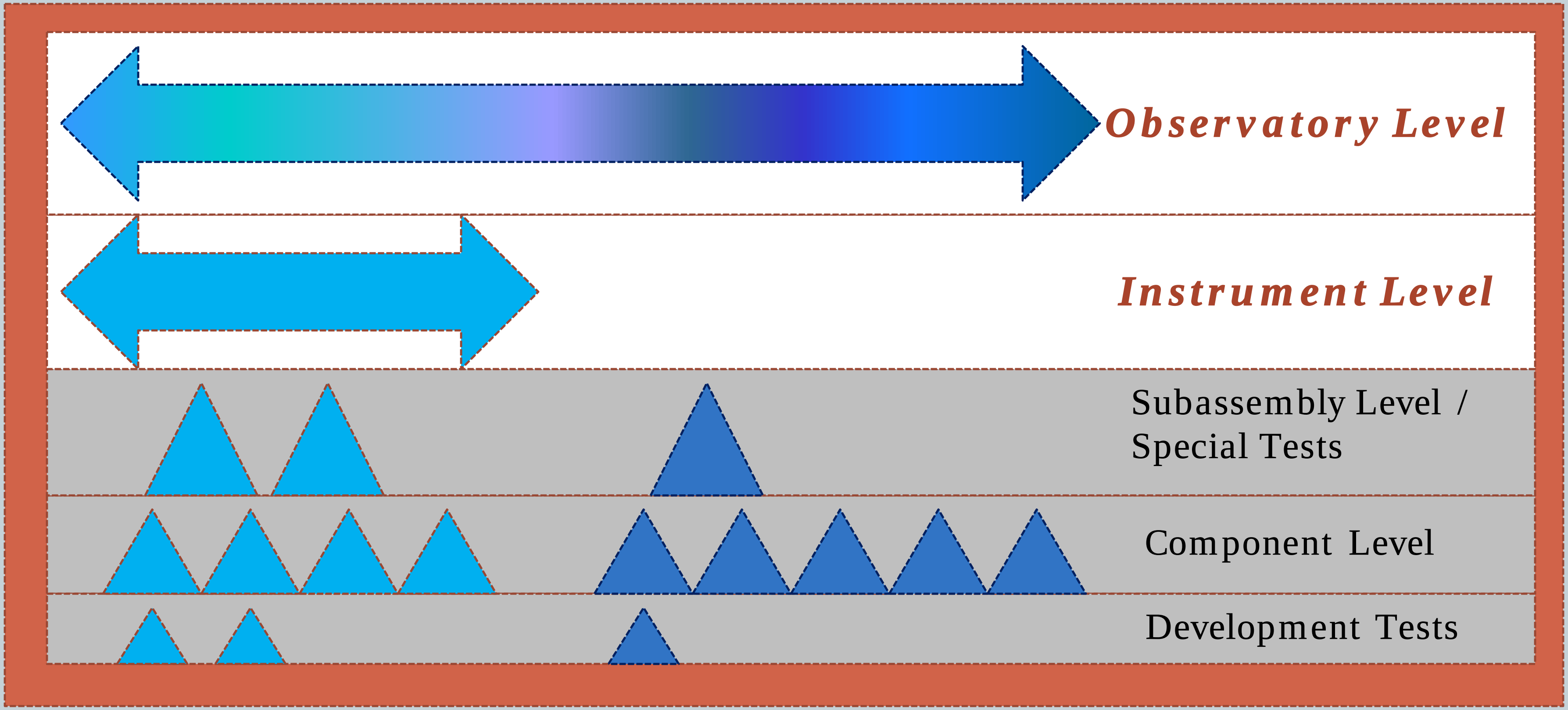


Examples from Flight Projects Throughout Presentation

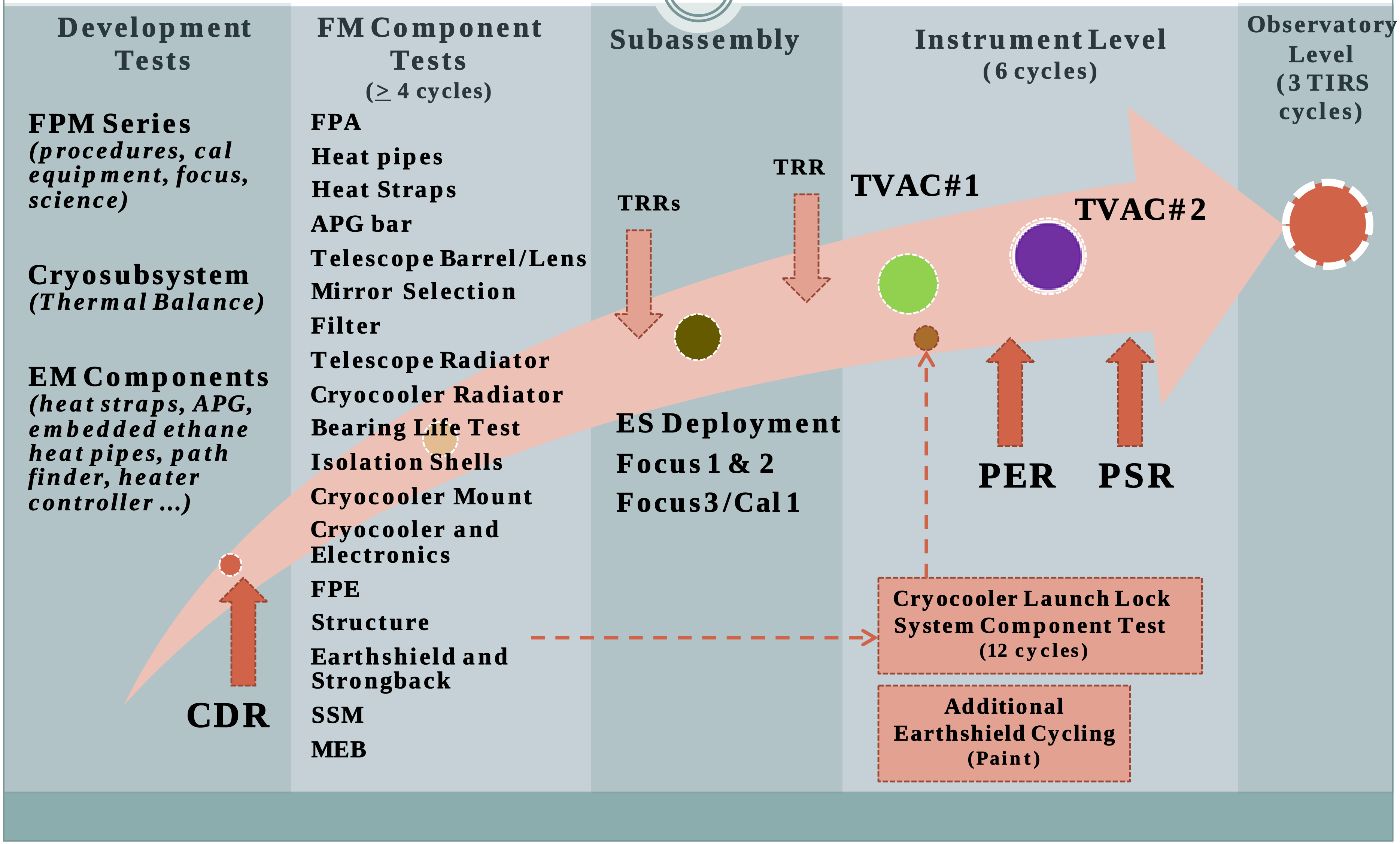
Thermal Vacuum Testing Overview

- Most complex and expensive test of the environmental test campaign
- Typically last test conducted (i.e. post-vibration & EMI)
- Requires coordination of all subsystems
- *Flight* Design may be effected by testing
- Detailed planning activities should begin at six-to-eighteen months prior to testing depending on complexity of test
- Planning begins at lower levels of testing to ensure requirements are verified:
  - Subsystem
  - Engineering
  - Performance
  - Science
  - Cycling/Turn-on
  - Bake-out
  - Thermal Balance
  - Operational Time

Levels of Testing



Levels of Testing
An Example: TIRS Thermal Test Program



Basic GEVS Requirements

Assembly Level	*Vacuum*	*Thermal Cycles*	*Dwell Time*	*Qualification Level*
Observatory	**<10^{-5} Torr**	**Four**	**≥24 hours**	**± 10^{o} C beyond AFT***
Instrument	**<10^{-5} Torr**	**Four**	**≥ 12 hours**	**± 10^{o} C beyond AFT***
Component	**<10^{-5} Torr**	**Four to Eight**	**≥4 hours**	**± 10^{o} C beyond AFT***

- There are **lots** of nuisances in GEVS. Consult with thermal PDL for full understanding of specific systems requirements (*Cryogenic, fixed set-point, in-air, etc*).
- Total of at least twelve cycles.
- Two hot/cold turn-on demonstrations per test (*A-B side/voltage*)
- ≥100 hrs hot , ≥ 100 hours cold, minimum of 350 hr trouble free in vacuum.
- Thermal Predicts versus AFT
  - Levels can be reduced based on thermal predicts if the model is correlated
  - Manufacturer's component qualification for some COTS may be wider than required for project. Work with thermal PDL to select higher level limits.

* AFT – Allowable flight temperature; Can be reduced to -5^{o}C for heater controlled systems with 70% duty cycle

Does Everyone Follow GEVS/Gold Rules Testing Requirements?

- **NO!** Requirements vary through-out NASA.
  - Philosophy evolved from missions types (interplanetary, Earth orbiting, manned flight)
  - May require an MOU or detailed ICD to satisfy requirements across multiple centers.
- Vendors utilize their internal testing requirements **unless** GEVS/Gold Rules are specified in the contract.
- Schedule and Budget may be effected by testing requirements.

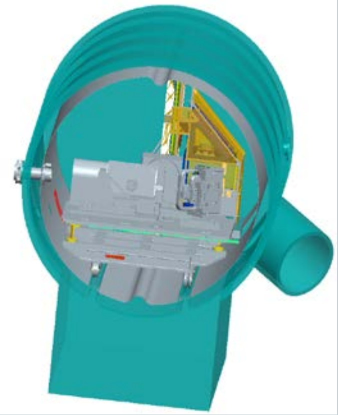
Early Planning

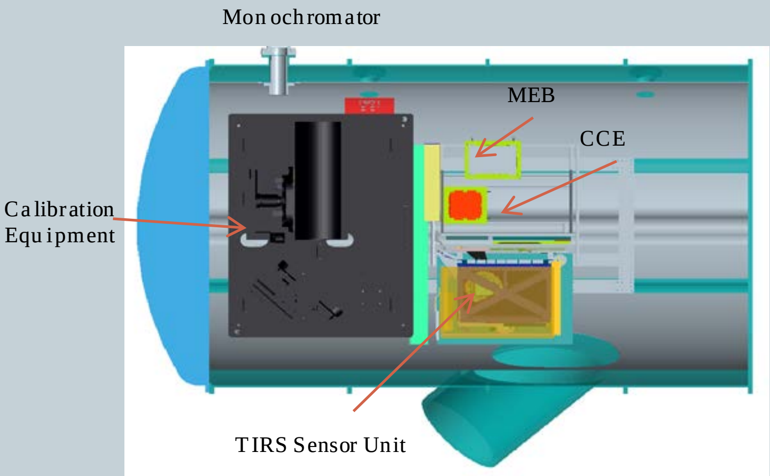
- **Select Chamber**
  - Physical Size/Availability
  - Feed-thrus/ports (electrical, thermal, optical)
  - Contamination
  - Special needs (optical, science)
  - If possible, design for multiple chambers
- **Determine Design Impact of Test Set-up**
- **Develop Cycling Plan**
  - Understand requirements
  - Hardware schedule
  - Restrictions at higher levels of assembly
- **Build Verification Plan**
  - Review requirements
  - Verify at lowest level of testing possible
- **Understand Risks**
  - Early Developmental Testing
  - Schedule-Cost versus Risk

BE FLEXIBLE AND PLAN FOR CONTINGENCIES!

Early Planning
Select Chamber: TIRS example

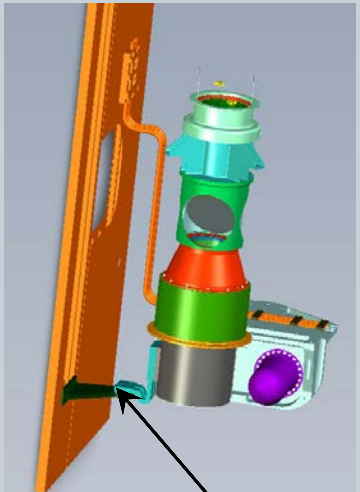
- Physically fit both the instrument and calibration equipment
- Provide consistent thermal noise background for FPM/FM tests
- Optical path for Monochromator
- Large number of electrical connectors
- LN2 feed-thrus for both Cal equip, cold plates, cryopanels
- Test Cryo-Refrigerator installation for tests prior to instrument level
- Clean tent/Cryopump for contamination control



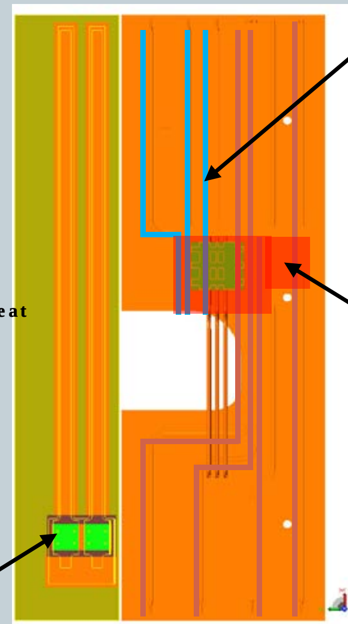


•Chamber 225 dedicated to TIRS during entire test program due to schedule and background requirements.
•Chamber selection influenced Cal equipment design.
•Chamber modifications: LN2 feedthrus, optical port cut, test cryo-refrigerator accommodations

Early Planning
Impact to Flight Design: TIRS example



APG/ Flexible Heat Strap
Used instead of Ethane
Transport Heat Pipes
For Vertical Test operation

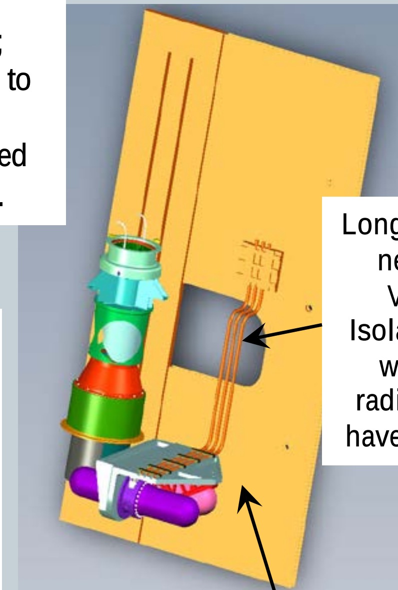


Three heat pipe working in Vertical; This was sufficient to reject cryocooler dissipation predicted by Thermal at CDR.

APG Doubler designed to attach mitigation heat strap during testing to carry the full cryocooler specification power of 180 W

Flight Blanketing designed to accommodate GSE strap

I/F with APG Bar Low so that Ethane Spreader Pipes would work in reflux mode



Long Pipe length needed for Vibration Isolation else i/f with the cc radiator would have been lower

Heat Source for Low so that Ammonia Transfer Heat Pipes would work in reflux mode

VERTICAL TEST CONFIGURATION FOR ALIGNMENT WITH CALIBRATION EQUIPMENT

Early Planning
Develop Cycling Plan: TIRS example

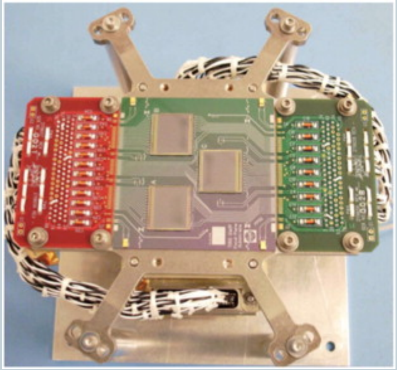
- **Originally** two LDCM tests; TIRS present only in the second test. Although it was planned to have 4 cycles in TVAC2 there was a contingency of only having 2 cycles since TVAC1 had 2 cycles. Therefore TIRS cycling plan was to have a minimum of 10 cycles prior to delivery.
- Vendor versus in-house (Vendors may test to standard wider limits)
  - TIRS potentiometer -65 to 125 C; system level limitation +50 C qualification; More than sufficient since max flight predicts ~ +10 C.
- Types of Components → May effect test program location for lower level cycling or set-up

ELECTRONICS	MEB CCE TMU(Cryocooler) FPE SSM	Cycling at component and instrument level over full qualification range
FIXED SET-POINT CRYOGENIC COMPONENTS	Telescope FPAs Cryo-shells/Shields Filter Telescope Radiator	Cycling at component and instrument level over full qualification range; Operational Cycles by environmental stress
STRUCTURAL MEMBERS	Structure/Scone Strongback Earthshield Cryocooler Radiator	Cycling for optical stabilization (structure) and to demonstrate survival with thermal-mechanical stress
DEPLOYMENT	Damper Potentiometer ERMs	Vendor tests at standard wider limits

Early Planning Build Verification Plan

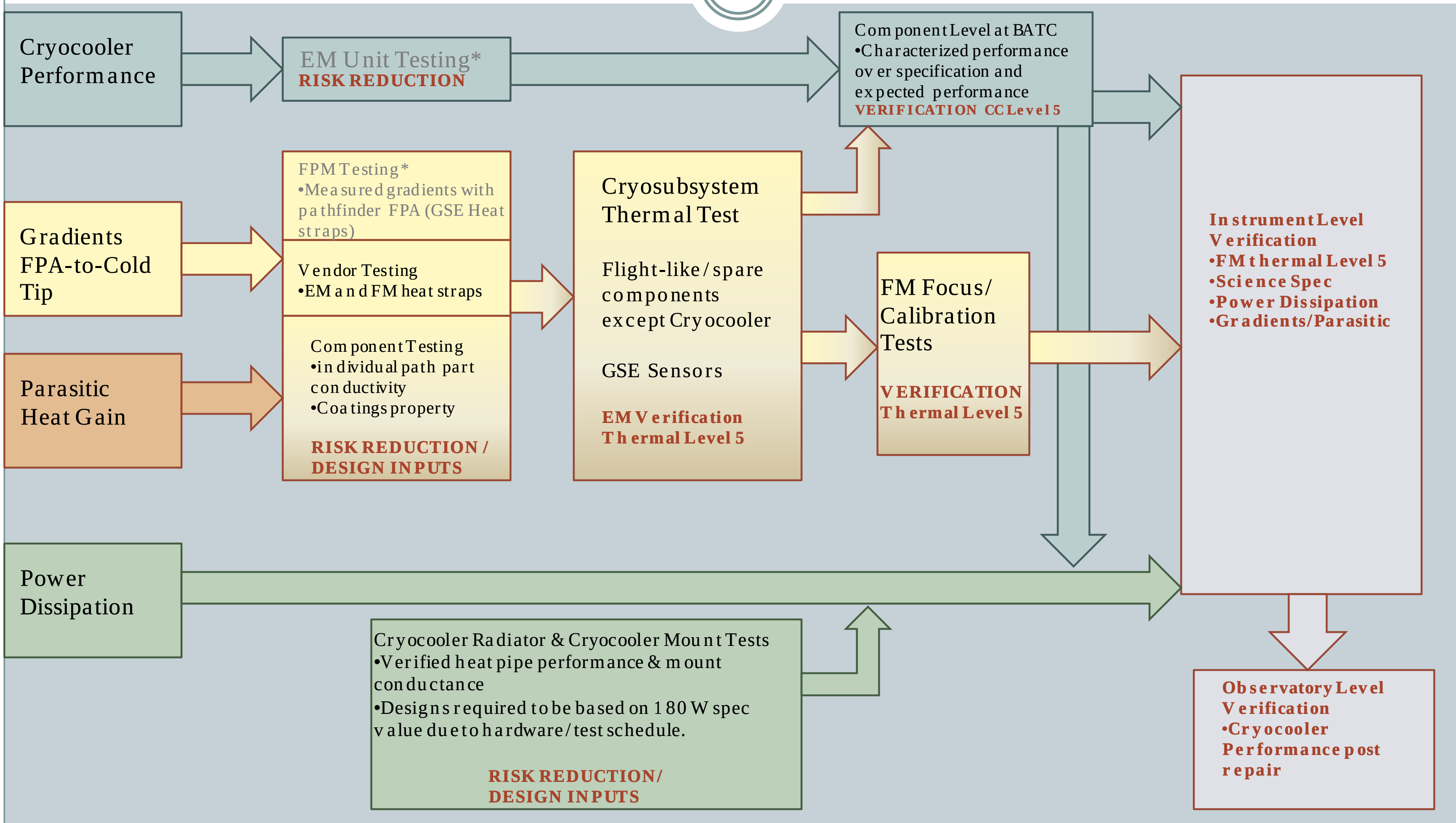
TIRS Example: Requirements, Risks, and Test Program Ensuring Focal Plane ≤ 43 K

- Requirement: FPA ≤43 K (Science Level 4 Spec & TIRS Thermal Design Level 5 Spec)
  - 2 W maximum parasitic load (Cryocooler Design Spec & TIRS Thermal Design Level 5 Spec)
  - 225 W maximum dissipation (Cryocooler Design Spec & LDCM-TIRS ICD)
  - 180 W maximum TMU dissipation (Thermal allocation for cryocooler radiator design)
- Identify what will be verified in TVAC testing and components
  - **Cryocooler performance**: Heat lift capacity
  - **Cold Tip Parasitic heat load** : FPA power, Thermal coupling to warm areas
  - **Gradient from FPA to cold tip**: Conductive path
  - **Power dissipation of CCE/TMU** : Function of parasitic load/gradient and cc performance
- Identify Hardware Designs Effected by Requirements
  - TMU/CCE (BATC), CCM, FPA (including mount/filter), Flexible Heat Straps, Cryocooler Radiator
- Develop Test Program based on Risk Factors/Schedule
  - Cryocooler component testing late in program due to aggressive schedule
  - Some FPM/EM hardware was not thermally representative but provided insight and risk reduction
  - Lower level testing (and analysis) provided good confidence that parasitic heat load was ~half the specification value and that the thermal link exceeded requirements. However schedule risk if the FM cryocooler or CSS thermal performance was different than EM units required that design of cryocooler radiator/CCM be based on the 180 Watt specification.



Early Planning Build Verification Plan (Continued)

TIRS Example: Requirements, Risks, and Test Program Ensuring Focal Plane $\leq$ 43 K



*Tests listed in grey were using hardware that were thermally different from flight hardware

Mid-Stage Planning

- Review requirements, and engineering/science functions to develop performance tests.
- Review requirements, thermal analysis, and higher level qualification plans prior to starting the component qualification program.
- Identify components that are not in test (solar arrays, flight battery, etc.)
- Review schedule and adjust test plan accordingly

For example: originally the TIRS earth shield deployment test was planned to occur after the integration of the optics/focal plane & cryocooler. However the hardware required for deployment (structure, strong back, earth shield) was available before the cryocooler delivery. The deployment test was shifted forward (prior to full integration) allowing TIRS to run focus/calibration testing concurrently thereby saving a month of schedule.

- Identify any long term lead items needed for testing. (simulators, cryopanels, cryorefrigerators, control systems, etc).

For example: on WMAP the heater control racks available in our facility had "bang-bang" thermostatic controllers. Science required high thermal stability; therefore we needed to develop new heater control rack which interfaced with facility operator controls. This took approximately one year to develop/build.

For example: SAM required a specialized chamber simulated mars atmosphere be built, certified, and integrated with building facility this process took several years.

Performance/Science Test Influences

When developing the scripts for and the placement of performance/science testing

- Environmental
  - Ambient versus at Temperature (i.e. cryogenic, high temp)
  - Vacuum versus in Atmosphere
  - Transition versus Plateau
- Mission Influences
  - Voltage
  - Spacecraft Side

Detailed Planning

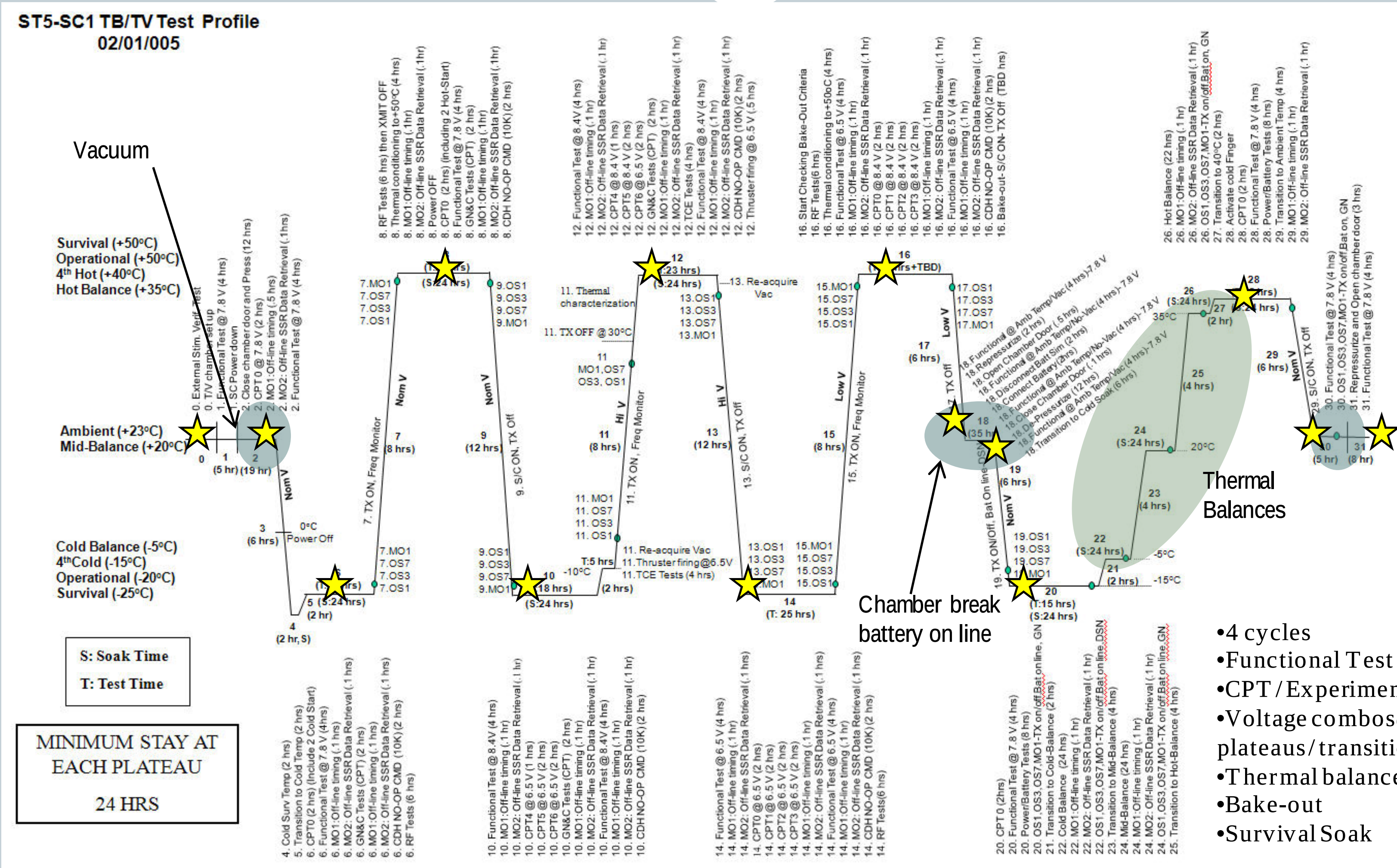
- Establish a Regular Meeting Schedule
  - Action Item List
  - GSE and Flight Hardware Status
  - Documentation Status
  - Personnel Requirements
- Develop the Thermal Profile
  - Thermal Qualification (temperature levels, duration, survival)
  - Turn-on/Removal of Power/Turn-off
  - Engineering and Science Performance Tests
    - Plateaus versus Transitions
    - A/B side Operation
    - Voltage
  - Hardware Check-out
  - Bake-out
- Determine GSE set-up
- Emergency Planning
  - Risk Tolerance
  - Flow Chart & Emergency Procedures
- Create Documentation

Detailed Planning
Typical Thermal Profile (Instrument/Observatory Level Test)

- Performance Testing
  - Aliveness, Short Form Functional, Long form Functional
  - Pre and Post test at ambient for comparison
  - At each plateau (SFF, LFF, or CPT); testing during transitions
  - Day in the Life Test
- Thermal Verification
  - Hot Op, Cold Op, Survival Balances (specific voltage; flight environment simulation)
  - Parametric Studies (Sensitivity)
  - Hardware Checkout – heaters, thermostats, cryocooler, TECs, heat pipes, etc.
- Thermal Qualification
  - Four thermal cycles, survival soak, hot turn-on (2x), cold turn-on (2x), power down
- Engineering Characterizations
  - Mechanism Operation, Controller Tests, Deployments, Software, Jitter
- Science/Calibration Tests
  - Dependent on mission; done at plateaus and/or transitions
- Contamination
  - Bake-out; Contamination Certification

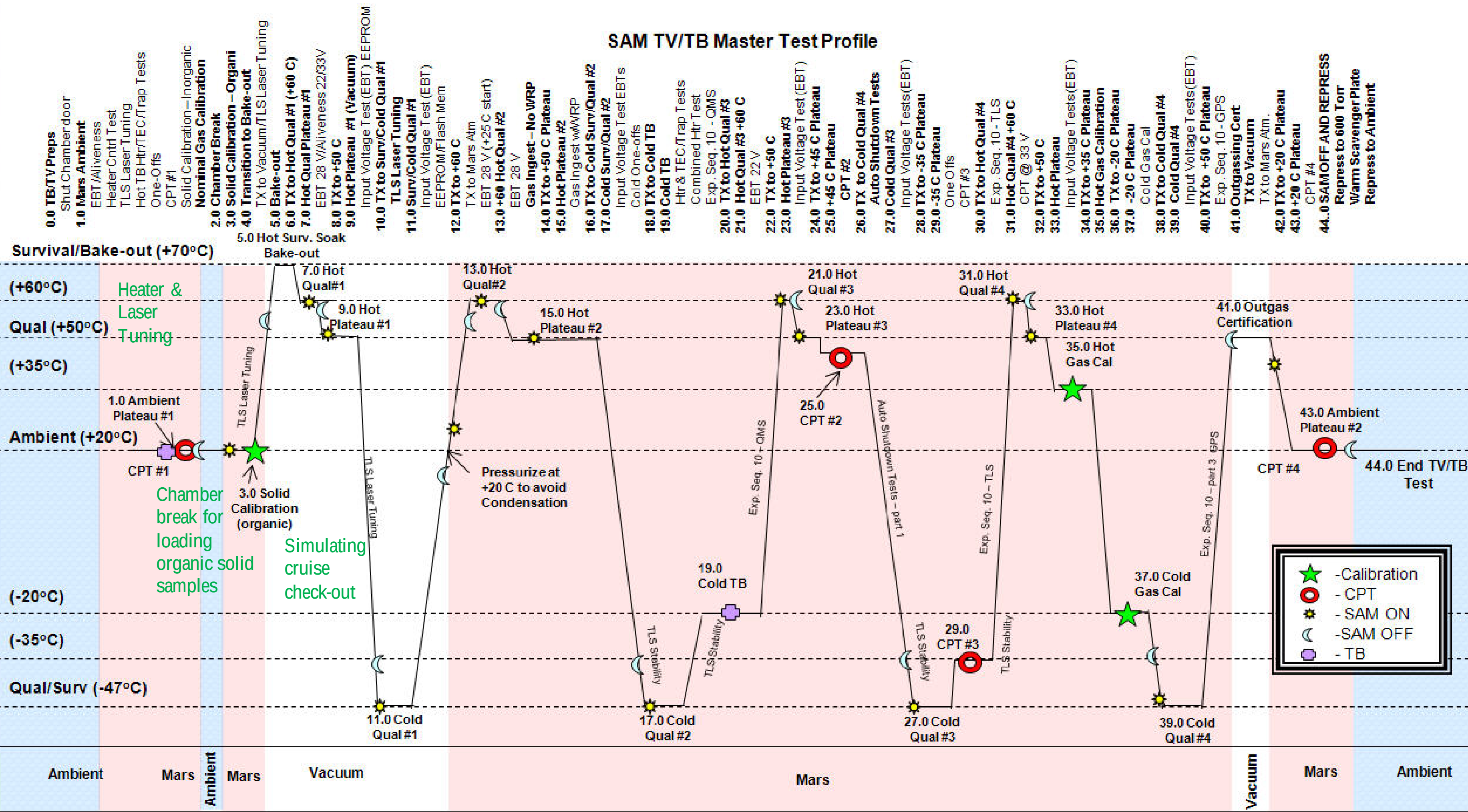
Note: specific testing is project dependent use as guideline only.

Detailed Planning Develop the Test Profile Example 1: ST5 Observatory TVAC



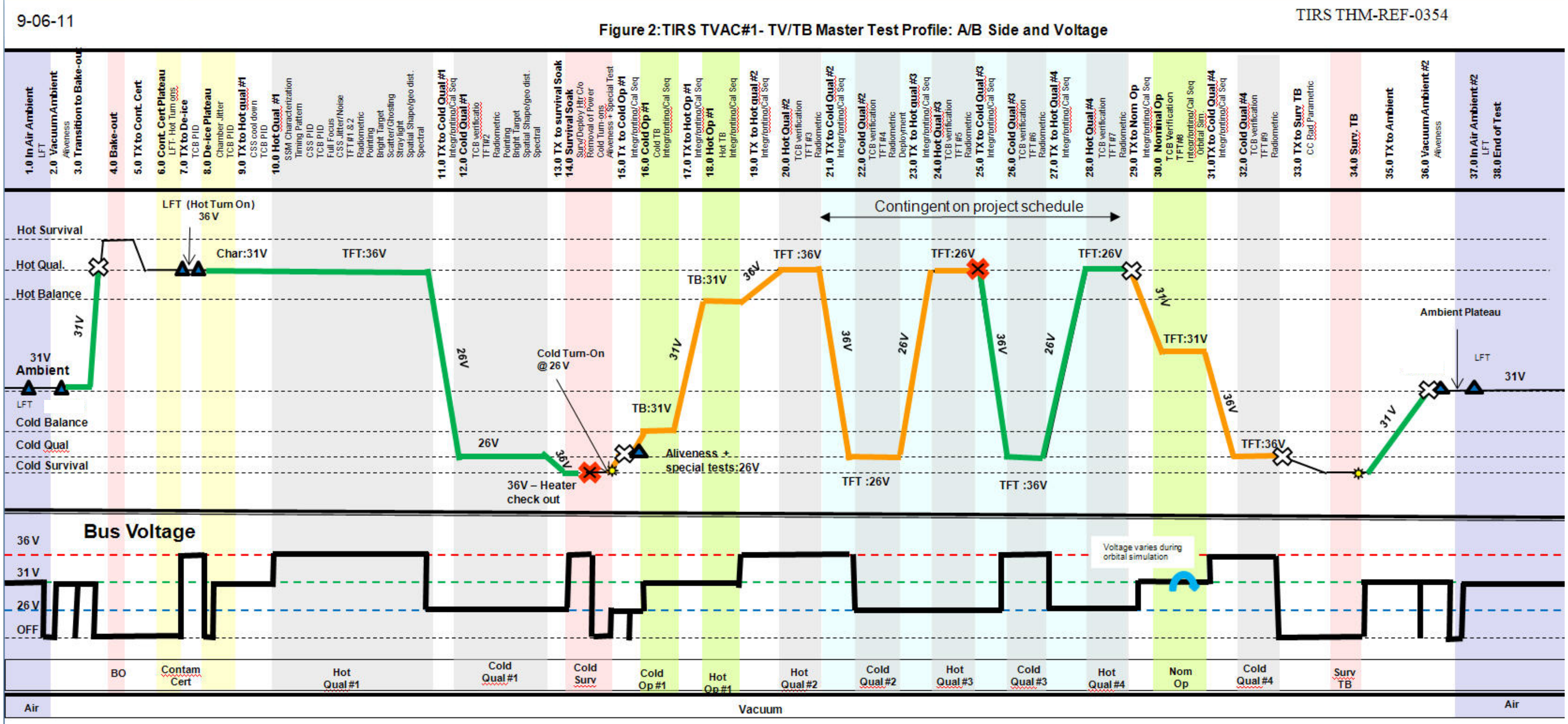
- 4 cycles
- Functional Test Baseline
- CPT / Experiment
- Voltage combos @ plateaus / transitions
- Thermal balances
- Bake-out
- Survival Soak

Detailed Planning Develop the Test Profile
Example 2: SAM Instrument Test 1



Detailed Planning Develop the Test Profile

Example 3: TIRS Instrument TVAC1 Pretest Profile (Voltage and A/B Side)



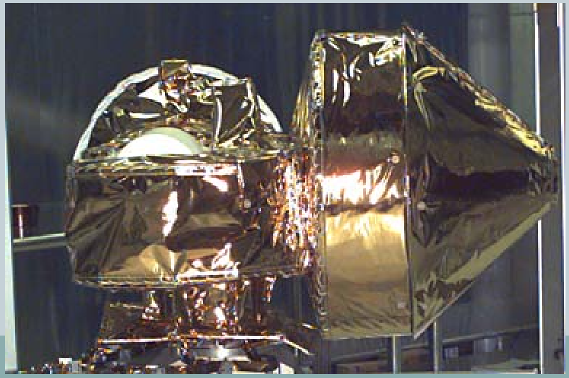
LFT – ambient operation functional
TFT - cryogenic operation functional

✖ Unannounced removal of power test
✧ Standard Power down (side change)

A side
B side
Off
A/B Test

Detailed Planning Testing during Transitions
Example: CIRS Instrument Testing

- **Question**: Why do you need to do performance testing during transitions? The extremes should "bound" the environmental conditions.
- **Answer**: Although the plateaus bound the environment they may not be imposing the worst-case gradients; Testing during transitions uncovers workmanship issues.
- **Example**: The first test of the Main Electronics Box on the CIRS instrument uncovered a workmanship issue with soldering of a component. The performance at the extreme temperatures was good; However a repeatable anomaly occurred at an intermediate temperature. The faulty solder joint was repaired and CIRS (Launch in 1997 on the Cassini Mission) has been collecting data on Saturn for the past 8 years... double its mission lifetime!

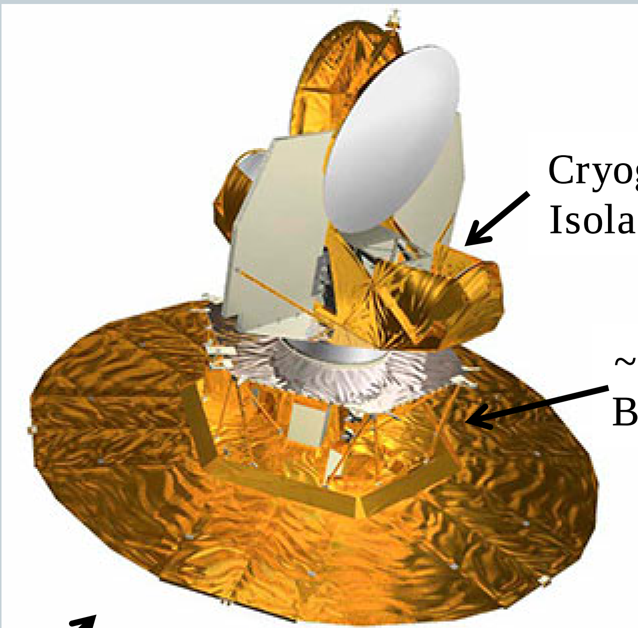


Detailed Planning Determining GSE Set-up

- Types:
  - MGSE (Scaffolding, Dollies, Slings, Accelerometers, etc.)
  - EGSE (Flight System, Simulators, Non-facility controllers, etc.)
  - CGSE (Scavenger plates, witness mirrors, QCMs, RGA, etc.)
  - TGSE/Facilities (Heater Control Racks, Test Sensors, TCUs, IR plates, Cryopanels, Cold plates, etc).
  - Science/Calibration
- Requirements:
  - Simulates flight environment
  - Drives temperature to qualification levels
  - GSE and personnel can fit around chamber (Floor plan)
  - Facility can support harnesses (Listing of connectors/feedthrus)
  - Facility can support cold plates/cryopanels (listing of plumbing feedthrus)
  - GSE and flight hardware integration feasible (Storyboard)

Detailed Planning Determining GSE Set-up

Example: WMAP Observatory Level Test TGSE Set-up Thermal Design Environments



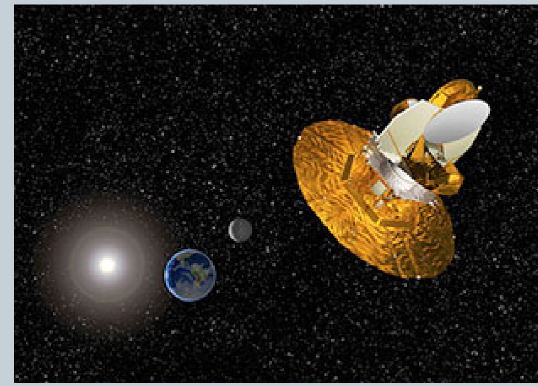
Cryogenic Instrument Isolated from S/C Bus

~ Room Temperature S/C Bus Shielded from Sun

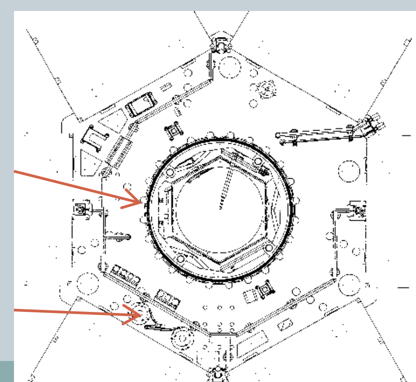
Solar Arrays, Medium Gain Antenna and Bottom Deck Facing the Sun

Solar Arrays did not fit in chamber

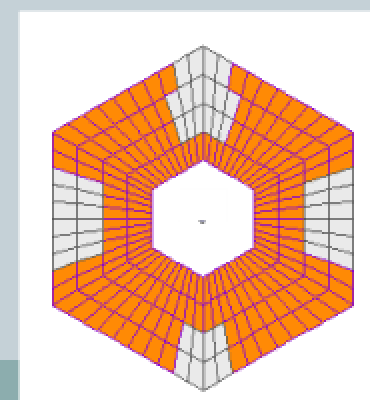
L2 Orbit



Bottom Deck

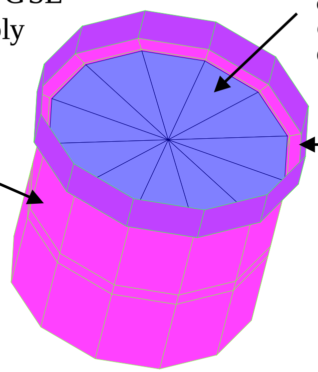


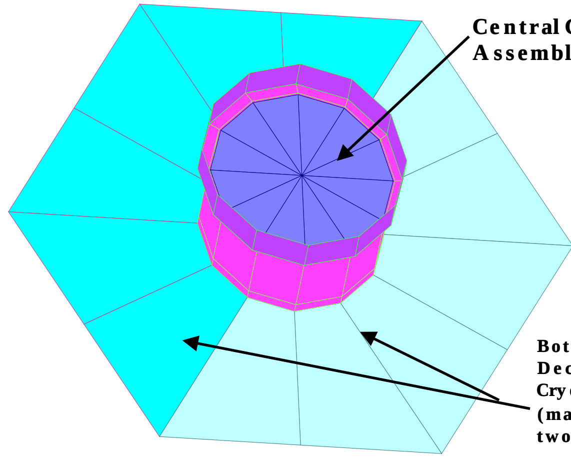
Silver Teflon Tape Pattern For Thruster Areas

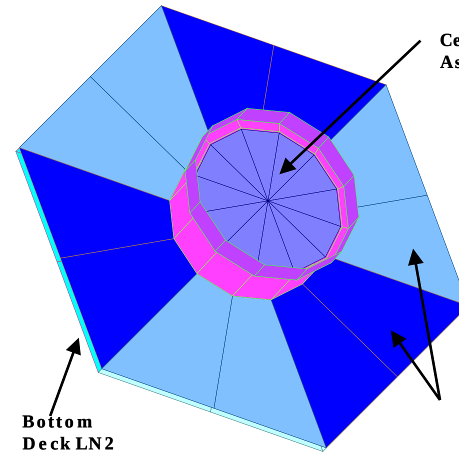


Detailed Planning Determining GSE Set-up

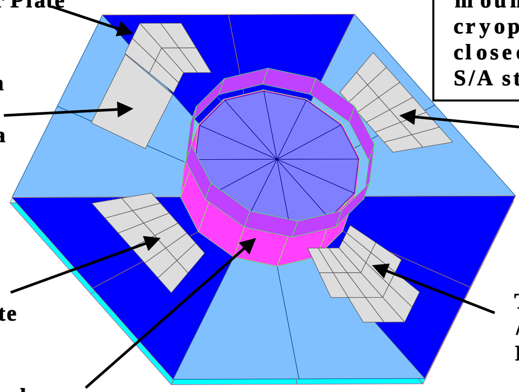
Example: WMAP Observatory Level Test TGSE Set-up Abbreviated Storyboard

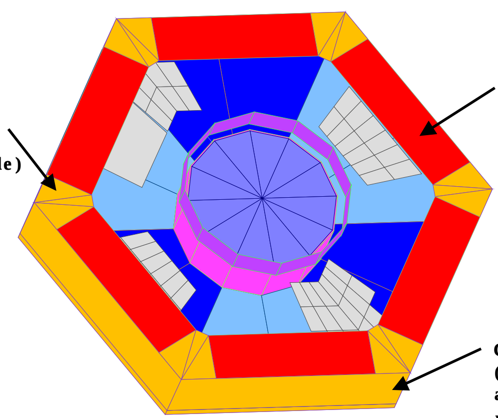




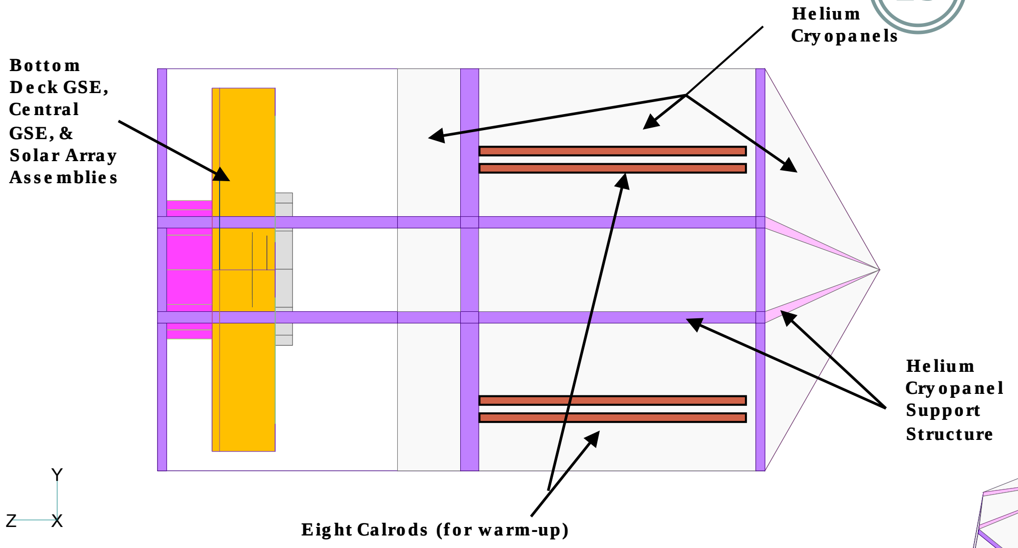


Note: Heater Plates are mounted to the bottom deck cryopanels. There will be MLI closeouts (not shown) to the S/A stubs and bottom deck

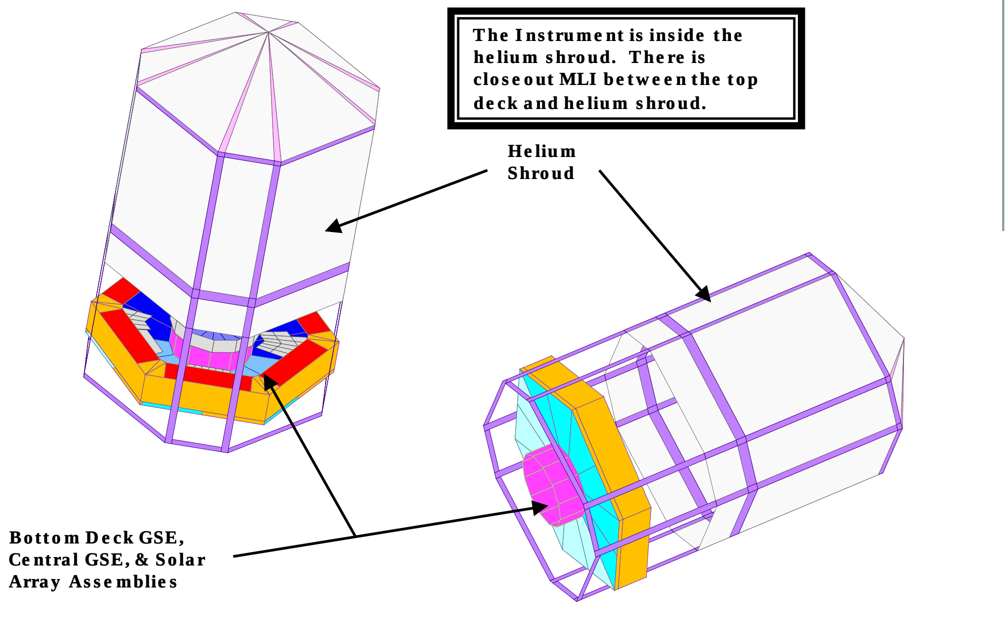




Example: WMAP Observatory Level Test TGSE Set-up Abbreviated Storyboard



Chamber at LN2



Detailed Planning
Emergency Planning – Anything Can Happen!

- Some Examples:
  - JWST OSIM Test → Loss of Facility Power (June 2012)
  - TIRS Instrument Level Test → Earthquake, Hurricane, and Fire (all within a couple of weeks time period)
  - SAM Test → Solenoid Issue (Mars Gas Pressure)
  - ST-5 Test → Sudden Loss of Chamber Pressure
  - WIRE Test → Cryopanel Valve Failure
  - CIRS Mirror Test → LN2 Cryogen Leak
  - CIRS Calibration Target Test → Ice Plug
  - UARS MMS Test → Thermal Conditioning Unit Failure
  - COBE DIRBE Test→ Loss of Facility Power

Several tests where GSE heater/power supply failed or severe snow storms/hurricanes resulted in using emergency procedures.

Detailed Planning
Emergency Planning & Risk Tolerance

- Establish contingency plan/procedures to ensure the test article's safety in case of:
  - Loss of Power (UPS; emergency generators)
  - Loss of Vacuum
  - Thermal GSE Failure (cryopanels, heaters, IR plate, TCU)
  - Chamber Control Failure
  - Flight Thermal Control System Failure
  - Flight Article Failure/Loss of Commanding
- Personnel safety and action
- Develop flow charts of actions
- Determine risk tolerance
  - Safety of Test Article
  - Schedule Impacts
- Implement redundancy based on risk tolerance

Flow Chart Example from ST-5 plan

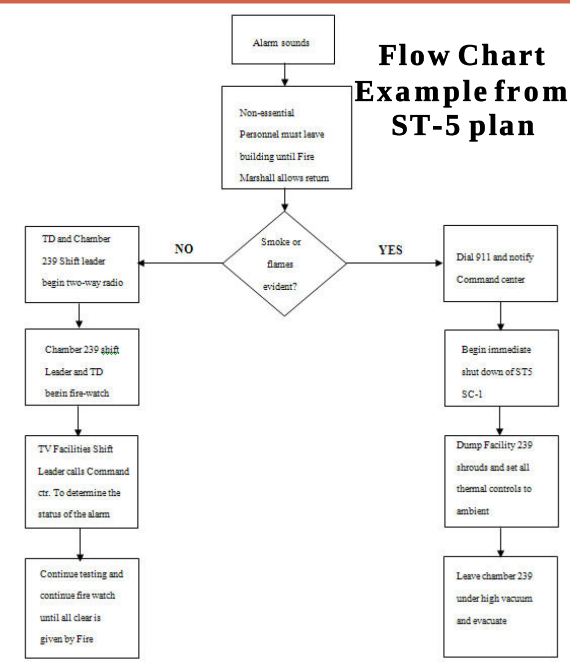


Figure 4.5.1: ST5 SC-1 TV/TB Test Building Fire Alarm and Evacuation

Detailed Planning
Example: TIRS Instrument TVAC2 Thermal GSE Redundancy

- Risk Tolerance was very low due to schedule. GSE Failures that needed a chamber break to repair would have resulted in large schedule delays (repairs plus cryogenic warm-up, additional bake-out, and cooldown). Hardware protection as well as providing environment for Science/Performance testing (TVAC levels) and Launch Lock Deployment were fully redundant.

	Primary	Redund.	Redundancy Type	Notes
Cryocooler Radiator Base, Zone 1/Zone 2	1-1	2-1	P	Additional protection for CC radiator +warm-up
CC rad heat block (GSE on Flight Rad)	1-2	2-2	F	Protects TMU / TVAC levels
CC Rad Cryo Panel	3-2	3-12	F	Warm-up and LL deploy
Earthshield stub Upper	1-4	N/A	N*	Thermal Balance
Earthshield stub Lower	3-10	N/A	N*	Thermal Balance
Hinge panels, Lower	1-5	2-12	F	Protects Damper/ TVAC levels
Hinge panels, Upper	2-8	3-9	F	Protects Potentiometer / TVAC levels
Telescope cryopanel	1-6	3-3	F	Warm-up and LL deploy
FPE panel	1-9	2-9	F	Protects FPE/ TVAC levels
Structure enclosure + X	2-3	3-4	F	Protects Structure from LN2 Walls (required for calibration background) and TVAC Levels
Structure enclosure -Y	2-4	3-5	F	
Structure Enc. + Z Upper	2-5	3-6	F	
Structure Encl. + Z Aperture	2-6	3-7	F	
Structure enclosure - Z	2-7	3-8	F	
MEB Heater Plate	MEB HTR	2-10	F	Protects MEB /TVAC levels
CCE Heater Plate	CCE HTR	2-11	F	Protects CCE/ TVAC levels
S/C Deck Simulator	1-7	1-8	F	Protects Mounting flexures/Optical Deck
Zero Q, SUDP Harness 1	1-10	N/A	N	Thermal Balance
Zero Q, SUDP Harness 2	1-11	N/A	N	Thermal Balance
Zero Q, MechDP Harness	1-12	N/A	N	Thermal Balance
BB Calibrator Heater Plate	BBCAL PRI HTR	BBCAL RED HTR	F	Protects BB Cal + Science Performance
Payload Table	3-10	3-11	P	Warm-up Only

F- Full P- Partial N- None

**Hinge panels will keep hardware safe*

Documentation

- Test Plan
  - Set-up, Test Profile Elements, Emergency Response, Personnel Responsibilities, Success Criteria, Limits
- Constraints
  - Flight and Test
- Procedures
  - Set-up/Integration, Moving/Lifting, Pretest Checks, Thermal Balance, Thermal Transitions, Functional/Science Testing
- WOAs
  - Step-by-Step Instructions/Procedure Identification

Good Documentation is Key to Successfully Conducting a TVAC test and Verifying Requirements!

Summary

- Start Planning Early!
- Understand Requirements →Develop Verification Matrix
- Design with Testing in Mind
- Review/Adjust Test Program Continuously
- Systems Team Should be Heavily Involved in Test Planning to Ensure that Requirements will be Verified

Acronyms

- AFT – Allowable Flight Temperature
- APG – Annealed Pyrolytic Graphite
- CCE – Cryocooler Control Electronics
- CCM- Cryocooler Mount
- CDR- Critical Design Review
- CGSE – Contamination Ground Support Equipment
- CIRS - Composite Infrared Spectrometer
- COBE – Cosmic Background Explorer
- CSS – Cryosubsystem
- EGSE –Electrical Ground Support Equipment
- EM- Engineering Model
- FM – Flight Model
- FPA – Focal Plane Assembly
- FPE – Focal Plane Electronics
- FPM – Functional Performance Model
- GEVS - General Environmental Verification Standard
- GSE – Ground Support Equipment
- GSFC - Goddard Space Flight Center
- ICD- Interface Control Document
- JWST – James Webb Space Telescope
- LN2 – Liquid Nitrogen
- MEB- Main Electronics Box
- MOU – Memorandum of Understanding
- MGSE – Mechanical Ground Support Equipment
- NASA - National Aeronautics and Space Administration
- OSIM - Optical Telescope Element Simulator
- PER – Pre-Environmental Review
- PDR- Preliminary Design Review
- PSR – Pre-ship Review
- SAM – Sample Analysis at Mars
- SES – Space Environmental Simulator
- SIRTF - Space Infrared Telescope Facility
- SMEX - Small Explorers Program
- SHOOT- Super-fluid Helium On-Orbit Transfer
- ST5 – Space Technology 5
- TEC – Thermal Electric Cooler
- TGSE – Thermal Ground Support Equipment
- TRACE - Transition Region and Coronal Explorer
- TIRS - Thermal Infrared Sensor
- TMU – Thermal Mechanical Unit
- TVAC (TV)- Thermal Vacuum
- TB – Thermal Balance
- TRR – Test Readiness Review
- UARS – Upper Atmosphere Research Satellite
- ULDB - Ultra-Long Duration Balloon
- WMAP - Wilkinson Microwave Anisotropy Probe
- WOA- Work Order Authorization
- XRS – X-Ray Spectrometer

Early Planning Build Verification Plan
TIRS Example: Requirements, Risks, and Test Program
Back-up Slide Requirements

LEVEL 3 – INSTRUMENT ICD

- TIRS-SC-280 The NTE internal power dissipations for the MEB and CCE shall be as shown in Table TIRS-SC-281. (MEB 65 W and CCE 49 W).

LEVEL 4 – INSTRUMENT REQUIREMENTS (TIRS-SE-SPEC-0003)

- FS-496 At the nominal operating temperature of 43 K, the FPA shall have a combination of the minimum Conversion Efficiency (CE) and Dark Current (ID) such that the predicted (NEdT) for the 10.8 (10.5-11.5um) micron band and the 12.0 um band (11.3-12.3) with a 300 K target is less than 0.33 K.
- FS-1012 The TIRS thermal control system shall meet the operating temperature and temperature stability as defined in table 3-8. The operational temperature of the non-science driven requirements are specified in TEVR. (partial requirement shown here due to space considerations)

LEVEL 5 – CRYOCOOLER REQUIREMENTS (TIRS-SE-SPEC-0013)

- CC-201 The Cooler shall provide 2 W of cooling power at its Second-Stage Load interface at an operating set-point temperature under 38 K given the Power Performance specified in Section 3.1.2 of this specification.
- CC-207 The Cooler shall meet the Cooling Performance specified in Section 3.1.1 of this Specification, at End Of Life (EOL) and a heat rejection temperature of 273K, while drawing less than 225 W of spacecraft bus power.

LEVEL 5 – THERMAL REQUIREMENTS (TIRS-SE-SPEC-007)

- THRM-414 The thermal subsystem shall minimize the parasitic heat gains to ensure the cryocooler cold stage can meet cooling performance requirements as specified in CC-201 of cryocooler requirement document.
- Systems sub-allocation of designing the cryocooler radiator to 180 Watts of dissipation in the TMU

Abstract

- Thermal vacuum testing is the most complex and expensive of the environmental test campaign. The Instrument/Observatory Level Test is the ultimate verification of the Engineering/Science requirements over the flight environmental range. Early planning is essential to ensure that all mission, project, and NASA Goddard requirements are met. Detailed planning requires the coordination of subsystem, software, science, and facility personnel to have a successful test program and guarantee the safety of the hardware. This presentation will provide an overview of the systems planning process, potential effects on flight design/verification, basic thermal test elements and test profile development. Real life examples from Goddard missions are used to illustrate key points.

About the Presenter

Ms. Mosier is senior thermal systems engineer with the NASA Goddard Space Flight Center. Working primarily on in-house projects during her 29 years at NASA, Ms. Mosier has been instrumental in the planning and execution of over 25 instrument/observatory level thermal tests. Ms. Mosier is currently assigned as the thermal systems engineer on the TIRS instrument for the LDCM mission that is scheduled to launch in 2013. During her career at Goddard she has worked on many challenging projects including COBE, UARS, XRS, GRS, SHOOT, CIRS, WIRE, TRACE, SMEX-lite, SIRTF, JWST, ULDB, LISA, WMAP, XRS, ST-5, SAM, and TIRS. This has afforded a wide-range of testing experience from cryogenics to high-temperature systems in addition to the standard spacecraft testing. Ms. Mosier has been an instructor for spacecraft engineering design course at the University of Maryland. She also developed and teaches a thermal design course at NASA for civil servants and support contractors. Ms. Mosier is currently working with the NASA Engineering and Safety Center's (NESC) to develop standard training materials for thermal testing and thermal design/analysis.