International Space Station Passive Thermal Control System Top Ten Lessons-Learned

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Introduction

- **The ISS program at the NASA Johnson Space Center (JSC) divides thermal engineering responsibilities into two groups:**
  - **The Passive Thermal Control System (PTCS) team is generally responsible for the thermal engineering and analysis of ISS systems and components**
  - **The Active Thermal Control System (ATCS) team is responsible for the specific equipment/subsystems that provide thermal conditioning via fluid flow (ammonia and water), including pumps, radiators, heat exchangers, tanks, and cold plates**
- **PTCS works closely with all ISS systems, e.g. ATCS, Communications and Tracking (C&T), Structures and Mechanisms (S&M), over the entire life cycle of each system's hardware**
- **The technical scope of this effort has provided valuable insight on a broad range of challenges, and many valuable lessons have been learned**

ISS PTCS, Top Ten Lessons

- **Ten areas have been selected in an attempt to maximize applicability to thermal engineering and analysis in general**
- **The lessons focus on the following areas:**
  1. **Requirements Development and Verification**
  2. **Temperature Limits**
  3. **Optical Properties**
  4. **Model Fidelity**
  5. **Modeling All the Physics**
  6. **Modeling Nominal and Off-Nominal**
  7. **Uncertainty Margin**
  8. **Temperature Sensors**
  9. **Heaters**
  10. **Operations and Sustaining Engineering**

1. Requirements Development and Verification

- **Concept of operations and design reference missions should be used to help drive and scope appropriate requirements**
- **Establishment of a program/project-level thermal control, verification, and analysis plan is highly recommended, including appropriate standards and best practices**
  - **Plans must addresss needs of the certification and environment test plans, component/system level, qualification/acceptance, proto-flight, etc. with a full understanding of applicable/planned test margins**
  - **Thermal model requirements, fidelity, and quantity should be dictated by the intended usage, e.g. requirements verification, test/flight validation, end-user requirements, integration, sustaining engineering**
  - **Model and analysis peer reviews should be planned and documented**
- **Deliverables over the entire life cycle of the hardware should be identified and agreed**
  - **Design cycle presentations and interim reports**
  - **Formal verification documents**
  - **Formal model release/revision schedules and documentation**
  - **Test plans and test support**
  - **Real-time and sustaining engineering support**
- **All necessary resources must be considered when defining budgets and schedules**
  - **Use deliverables to define budgets and schedules to be negotiated with program/project customers**
  - **Fully consider necessary software, workstation, and critical skill resources to address verification scope and methods**

2. Temperature Limits

- Determine if temperature limits are already defined per component specifications, previous applications, etc. or if limits are to be defined for the specific application
- Determine where temperature limits apply
  - Structural or thermal interfaces, baseplates, internal cards, etc.
  - Limits may also arise from structural, fluids, contamination, and life considerations
  - Consider impacts to model fidelity needs, model validation, and test requirements
  - Understanding of where temperature limits apply, how hardware may be tested, and the likely instrumentation for test and flight is critical
- All critical model nodes/surfaces should have limits identified
  - Assignment of critical nodes should address correspondence with planned test and flight sensor locations
- Limits should ultimately be deemed certified for all operational and non-operational modes, survival, and start-up
- Temperature limits must be included in formal configuration control

3. Optical Properties

- **The optical property approach should be defined in verification/analysis plans**
  - **Solar absorbtance and emittance**
  - **Transmittance, e.g. windows, woven materials**
  - **Properties should be considered for specification and verification by test or measurement**
- **Optics require robust management and configuration control**
  - **Ensure consistent usage for surface treatment types and processes**
- **Designs and models should also consider optics of internal or covered surfaces that may be exposed for maintenance, replacement, or other unplanned scenario**
- **Beginning-of-life (BOL) values should be based on measurements whenever possible**
  - **Additional consideration of build tolerance and bias for design verification (e.g. "cold bias" BOL) may be warranted**
  - **Initial mission analysis should be based on measurement of flight hardware prior to launch ("nominal" BOL)**
- **End-of-life (EOL) should be based on expected degradation sources**
  - **Ultra violet (UV), atomic oxygen (AO), and other contamination sources over specified life, and applicable test data, with additional bias as warranted for design (e.g. "hot bias")**
  - **Degradation versus time should be defined with the best available data**
- **Optics data may need to be re-verified via test or measurement after material or process changes**

4. Model Fidelity

- Strong model advocacy is critical in early planning and funding stages to define fidelity and quantity requirements appropriate for the entire life cycle of the hardware
- Competing goals to maximize detail and optimize computation time can be met with a suite of models
  - Consider proper configuration control and timing of model updates, e.g. major design milestones, final verification closure, etc., with understanding of the necessary additional resources
- PTCS has generally defined three levels of fidelity, 1) simplified, 2) reduced, and 3) detailed, and the following examples are offered:
  - Simplified (~node/surface count 10's)
    - Early trades, e.g. optics, heater sizing, heat balance
    - Integration, e.g. ISS vehicle-level, ISS external cargo sites
  - Reduced (~node/surface count 100's)
    - Early trades, e.g. optics, heater sizing, heat balance
    - Design trades, feasibility, large case studies, e.g. environment screening
    - Integration, e.g. launch vehicle external cargo attachments
    - Model validation
  - Detailed (~node/surface count 1000's)
    - Design verification and requirements closure
    - Sustaining engineering and anomaly resolution
    - Model validation

4. Model Fidelity (2)

- **Reasonable increases in detailed model fidelity, beyond needs driven by specific requirement verification, are recommended**
  - **Fidelity geared solely toward requirement verification may not be sufficient for operations support, failure response, etc.**
  - **Fidelity should encompass all operational and non-operational modes, including launch, on-orbit, and off-nominal configurations**
  - **All heat dissipation loads and modes must be simulated over the full range of voltage**
  - **Fidelity may also be driven by temperature offsets from critical nodes to sensor locations**
- **PTCS has refrained from use of the phrase “model correlation”, as sufficient measurement data (e.g. lab, test, flight) is rarely available or attainable**
  - **A more pragmatic “model validation” approach, targeting specific areas, is recommended**
- **Model validation can be achieved in several ways**
  - **Thermal vacuum tests using development units with additional instrumentation**
  - **Thermal vacuum tests at component/subsystem level**
  - **Thermal tests when natural convection artifacts can be minimized/reconciled, e.g. foam insulation, enclosures**
  - **Early breadboard-level measurements of complex power architectures, e.g. to refine converter efficiencies**

5. Modeling All the Physics

- **PTCS advocates the notion of modeling all the physics as a systems engineering approach to modeling, particularly for detailed models**
  - **Many modeling deficiencies have been a result of over-simplification, including missing detail in regard to the actual physics of the hardware function**
  - **Consider a multi-disciplinary approach including the needs of various stakeholders and systems**
  - **Multi-system aspects include installation, configuration, crew, and loads constraints, power distribution, fluid mechanics, condensation, contamination, and structural stress and fatigue/life**
- **PTCS has also had experience with anomalous thermal cover configurations (e.g. blankets, shrouds) on flight hardware**
  - **Due to late fit issues or inadequate retention (often detected as sagging just prior to launch) or simply inaccurate drawings**
  - **Inspections/walk-downs of flight hardware instituted early in the ISS assembly phase proved to be valuable**
  - **The thermal team should have signature authority on thermal cover drawings**

6. Modeling Nominal and Off-Nominal

- **Experience has shown that concept of operations and design reference missions do not necessarily capture all the configurations that may drive design and model requirements**
- **Requirements should consider all possible configurations**
  - **Maintenance, removal and replacement (R&R)**
  - **Off-nominal or contingency flight trajectories or maneuvers**
  - **Higher-level system/vehicle off-nominal or contingency configurations including rotating elements, e.g. antennas, radiators, solar arrays**
  - **Again, PTCS advocates for a strong systems engineering approach**
- **Consider explicit modeling of fault tolerance and redundancy attributes to enable discrete assessments, e.g. for failure or anomaly resolution**
- **Fluid systems may be vulnerable to shut down resulting in loss of cooling, stagnant fluid, and isolated fluid lines/volumes**

7. Uncertainty Margin

- **A formal uncertainty margin approach must be baselined early in a program/project**
  - **Uncertainty margin in this context is the additional margin placed on the definition of acceptance test temperature limits for flight hardware**
- **ISS verification employed a somewhat standard bounding assumption approach**
  - **Critical to this approach was the verification to full flight attitude/trajectory envelopes**
  - **Use of flight envelopes resulted in more extreme temperature predictions, which in most cases provided sufficient margin to flight data, with five to ten degrees C margin typical**
  - **Further implementation of margin would have been difficult, considering the Space Station Freedom (SSF) heritage of many systems and the design for a low inclination orbit**
- **ISS was asked to consider introduction of a formal uncertainty approach after the Space Shuttle Columbia accident, but cost was deemed prohibitive**
  - **ISS did renew scrutiny in regard to model usage consistent with model development intent, e.g. a specific design or requirement verification, and any inherent limitations this may impose**
  - **Standard ISS practice is to scrutinize model usage, particularly for anomaly resolution or new applications**
  - **PTCS does pursue uncertainty margin via study of critical engineering parameter ranges, most often as part of an anomaly resolution effort**
- **Recent ISS projects as well as commercial vehicle programs have begun implementing uncertainty margin**
  - **More standard or common approaches are needed, particularly for exceptions or additional tailoring due to model validation**

8. Temperature Sensors

- **Temperature sensor requirements must be defined early in a program/project**
  - **Consider quantities and locations applicable and necessary for all operation and non-operation modes through the life cycle of the hardware**
- **Temperature sensor calibration must be under configuration control**
  - **Facilitates re-visitation as needed, e.g. changes due to new cabling/wiring, relocation of hardware, or other configuration updates**
- **Thermal models and analysis should dictate strategic alignment of sensor locations in terms of where temperature limits apply and where test and flight instrumentation is planned**
  - **Minimize reliance on large temperature sensor offsets**
- **PTCS advocates testing to confirm/reduce sensor errors when possible**
  - **Large sensor errors can be problematic and may complicate verification and certification margin approaches**
- **Management of temperature sensor errors and offsets is critical to defining sensor "redlines" for operations**
  - **ISS defines "redlines" as a limit not to be exceeded after accounting for errors and offsets**
  - **The definition of sensor redlines must be under configuration control**

9. Heaters

- **ISS has experienced numerous failures of film heaters with high power densities**
- **Failures have occurred with densities in the eight to sixteen Watts per square inch range**
    - **Failures tended to occur early in operational life, often during initial heater cycling**
    - **Failures most likely a result of workmanship issues leading to heater debond, burnout, and an open circuit**
- **While qualification thermal vacuum testing was often performed to verify design, acceptance thermal vacuum testing on flight hardware, critical for workmanship screening, was not**
- **ISS established a not to exceed three Watts per square inch criteria**
    - **Level is considered sufficiently low to enable heaters to withstand voids in bonding without heater failure**
- **Criteria also addresses:**
    - **No expectation of perfect heater installation, i.e. installation without risk of voids**
    - **Acceptance thermal vacuum testing for installation workmanship may be cost prohibitive or not possible**
    - **Post-test visual inspection may not be possible**
    - **Visual inspection cannot reliably detect imperfections that may be a prelude to failure**
- **Additional guidelines for applications where high power densities are required and especially when testing is not possible:**
    - **Implement additional heater element heat sinks, e.g. high emittance tapes or plates**
    - **Increase heater circuit power margins**
    - **Ensure robust redundancy and consider exceeding typical fault-tolerance requirements**

10. Operations and Sustaining Engineering

- **Operations planning analysis, also referred to as mission, date, or event-specific analysis was critical to the ISS assembly phase, and remains critical today**
  - **Events such as removal and replacement, delivery and installation tend to require hardware to be in a vulnerable state, e.g. unpowered or a temporary configuration**
  - **There is tremendous value in the ability to limit analysis parameters which in turn lends more feasibility to the definition of constraints and contingency responses, particularly for highly choreographed events such as space walk or robotic timelines**
  - **Specificity allows for reduced analysis case matrices, more efficient usage of resources, and the ability to respond more quickly to operational changes**
- **A related aspect to event-specific analysis is failure response, where the event is a component failure or an off-nominal or unplanned configuration**
  - **A pragmatic approach is required to provide a timely response for near-term plans, both safing of the vehicle as well as urgency of the next required response and consequences of the next worst failure (NWF)**
  - **Recall that a critical question in preparation for any failure or off-nominal configuration response is the suitability of the available thermal models**
  - **Once the vehicle is safed and the NWF impacts are addressed, more detailed assessments for long-term planning can begin, where a much wider range of conditions can be fully considered**

10. Operations and Sustaining Engineering (2)

- **Performance trending is critical to monitoring of hardware and system health**
  - **Trending may provide insight via unexpected signatures that may be a prelude to a limit violation or a failure**
  - **Trending also presents a unique opportunity for additional model validation under realistic flight conditions not attainable in test**
- **ISS as a large, long-term enterprise has the additional challenge of model and software maintenance through the sustaining phase**
  - **ISS is also a large integration enterprise, and models are exchanged among many users including contractor, international partner, and science teams**
  - **A central configuration control is maintained of all common-use and deliverable ISS thermals models**
- **Model updates for common-use models are provided with guidance for implementation**
  - **Guidance pertains to specific team needs and consideration of the hardware life cycle status, e.g. requirements definition, design cycle, verification, or sustaining phase**
- **ISS requirements also dictate software compatibility requirements for deliverables**
  - **Software updates are carefully considered and scheduled**

Conclusions

- This paper has offered a range of real world PTCS lessons with a recurring theme that thermal teams are critical stakeholders that must be engaged in the early definition phase of programs/projects
- The entire hardware life cycle must be considered in order to properly define scope and budget
- A systems engineering approach to modeling, not limited by specific requirement verification objectives, is recommended

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