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

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The International Space Station (ISS) has been on-orbit for nearly 20 years, and there have been numerous technical challenges along the way from design to assembly to on-orbit anomalies and repairs. The Passive Thermal Control System (PTCS) management team has been a key player in successfully dealing with these challenges. The PTCS team performs thermal analysis in support of design and verification, launch and assembly constraints, integration, sustaining engineering, anomaly and failure response, and model validation. This effort is a significant body of work and provides a unique opportunity to compile a wealth of real world engineering and analysis knowledge and the corresponding lessons-learned. The PTCS lessons encompass the full life cycle of flight hardware from design to on-orbit performance and sustaining engineering. These lessons can provide significant insight for new projects and programs. Key areas to be presented include thermal model fidelity, verification methods, analysis uncertainty, and operations support.

I. Introduction

THE ISS program at the NASA Johnson Space Center 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, whereas the Active Thermal Control System (ATCS) team is responsible for the specific equipment and subsystems that provide thermal conditioning via fluid flow, e.g. ammonia and water, and includes pumps, radiators, heat exchangers, tanks, and cold plates. The PTCS team works closely with all ISS system teams, 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. Ten areas have been selected for this paper in an attempt to maximize applicability to thermal engineering and analysis in general.

II. Top Ten Lessons

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. Heaters
8. Uncertainty Margin
9. Temperature Sensors
10. Operations and Sustaining Engineering

A. Requirements Development and Verification

Concept of Operations or Design Reference Missions should be used to help drive and scope appropriate requirements. PTCS advocacy is needed early in the program/project definition phase, and resulting analysis and verification methods/plans should ensure consistency with program/project requirements and expectations, especially test requirements and margins, uncertainty margins, model validation, and fault tolerance. The

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establishment of a program/project-level thermal control and analysis plan is recommended, including appropriate standards and best practices. Care should be taken to ensure any template requirements and verification methods, e.g. analysis, test, measurements, also address unique system/discipline aspects including crew interfaces, tracking systems, fluids, robotics, structures, including fatigue and life, and contamination.

PTCS verification is predominately by analysis, so expectations for model requirements and verification plans are critical, beginning with defining the types of work, including one or more of the following: concept feasibility/trades, development units and test, design cycle, e.g. Systems Requirements Review (SRR), Preliminary Design Review (PDR), Critical Design Review (CDR), requirements verification, certification, and test support. While the certification plan is defined at the program/project-level, more specific environment test plans may exist at the component/system level, e.g. qualification/acceptance, proto-flight, experiment/payload, with applicable test and uncertainty margins. Definition of margins is critical to the definition of temperature limits.

Model requirements, fidelity, and quantity should be dictated by the intended usage, e.g. requirements verification, test/flight validation, deliverable and end-user requirements, integration or sustaining needs. Inquiries into the past efforts of vendors/customers may reveal useful information, e.g. existing models, particularly for existing customer furnished hardware, performance data from test or flight, and lessons-learned.

Model and analysis peer reviews should be planned with schedule margin to account for the disposition of findings and necessary updates. Peer reviews conducted outside of the program/project team may prove beneficial.

Deliverables over the entire life cycle of the hardware should be identified and agreed to, including concept of operation or design reference mission documents, requirements documents, design cycle presentations and interim reports, formal verification document(s) and model(s) release/revision schedules, model documentation, test plans, test support, safety reviews, and sustaining engineering support.

Lastly, all necessary resources should be considered when defining budgets, e.g., software, workstation, and critical skill resources must be fully understood so that accurate and realistic budgets and schedules can be defined and negotiated with program/project customers.

B. Temperature Limits

First, determine if any temperature limits are already defined per component specifications, previous applications, etc. or if limits are to be defined for the specific application. Temperature limits should be deemed certified and defined for all operation and non-operational modes, survival, and start-up. Note that limits may also arise from structural, fluids, contamination, and life considerations.

Second, determine where temperature limits apply, e.g. structural or thermal interfaces, baseplates, internal cards, etc. and consider how this may drive model fidelity needs, model validation, and test requirements. The understanding of where temperature limits apply, how hardware may be tested, and the likely instrumentation for test and flight is critical.

Consider assignment of model critical nodes to include correspondence with planned or existing flight sensor locations, and test locations in order to minimize need to define temperature offsets if necessary. All critical model nodes/surfaces should have limits identified.

Finally, all temperature limits should be considered for formal configuration control.

C. Optical Properties

Robust management and configuration control of surface treatment optical properties, specifically solar absorbtance and emittance is critical. These properties should also be considered for specification and formal verification by measurement.

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”) 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), out-gas and other contamination sources, and applicable test data, with additional bias as warranted for design (e.g. “hot bias”). Ideally, degradation versus time should be defined with the best available data.

The optics approach should be defined in appropriate analysis plans for consistent usage. Designs and models should also consider optics of internal or covered surfaces that may be exposed for maintenance or replacement.

Lastly, optics data may need to be periodically re-verified via measurement or test after material or process changes.

D. Model Fidelity

Strong model advocacy is critical in early planning and funding stages to define model fidelity and quantity requirements appropriate for the entire life cycle of the hardware. While multiple models may be appropriate, they need not all be formal deliverables.

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 external cargo sites
  - Integration, e.g. launch vehicle external cargo attachment
- Reduced (~node/surface count 100’s)
  - Integration, e.g. launch vehicle external cargo attachment
  - Design trades, feasibility, large case studies, e.g. environment screening
- Detailed (~node/surface count 1000’s)
  - Design verification and requirements closure
  - Sustaining operations and anomaly resolution

For detailed models, PTCS advocates reasonable increases in model fidelity beyond needs driven by specific requirement verification, as model development and fidelity geared solely toward requirement verification may not be sufficient for operations support, anomaly resolution, etc. For example, an ISS common practice was to analytically verify components at a base plate or cold plate interface only, sacrificing component detail as necessary due to higher-level model integration limits. The competing goals to maximize detail and optimize computation time can be met with a suite of models. Model fidelity should encompass all non-operatioanl and operational modes, including launch and on-orbit configurations, and off-nominal configurations. All critical heat transfer paths require sufficient fidelity.

All heat dissipation loads and modes must be simulated including standby loads. Sensor and thermostat location accuracy can be critical, especially for accurate prediction of duty cycles for large heater systems. A full understanding is needed of sensor offsets to critical component areas and model nodes as well as the coldest and hottest locations of interest within the model.

Model validation can be important, especially to reduce uncertainty in areas deemed critical. The PTCS team has refrained from use of the term correlation, as sufficient measurement data (i.e. lab, test, flight) is rarely available or attainable. These limitations warrant a more pragmatic validation approach, e.g. a limited validation targeting specific areas. Opportunities to balance the inevitable cost and schedule aspects must be considered, as a thermal vacuum, thermal balance test, especially on a large scale, may not always be practical. Model validation of critical interfaces can be achieved in variety of ways.

- Thermal vacuum tests with additional instrumentation best accomplished during development testing
- Thermal vacuum tests at component/subsystem level
- Thermal tests if/when ambient convection artifacts can be minimized or reconciled, e.g. foam insulation
- Early breadboard-level measurements of complex power architectures, e.g. to refine converter efficiencies

E. Modeling All the Physics

PTCS advocates the notion of modeling all the physics as a systems engineering approach to modeling. The PTCS team has discovered many modeling deficiencies to be a result of over-simplification including missing detail in regard to the actual physics of the hardware function or the lack of a multi-disciplinary approach. Often the needs of stakeholders across multiple disciplines are not fully considered in the modeling assumptions and approach, e.g. thermally driven areas of fidelity may not be suitable for other stakeholders.

Multi-system aspects include installation constraints, configuration constraints, crew constraints, loads constraints, power distribution, fluid mechanics, condensation, contamination, and structural stress and fatigue/life considerations. In addition, appropriate integration of customer furnished hardware, particularly where there has been a lack of or insufficient modeling in the past. A particular area of concern has been exposed interfaces and fixtures, e.g. electrical and fluid connections, and robotic interfaces. PTCS advocates for a strong systems engineering presence in all programs/projects.

PTCS has also had experience with thermal cover configurations on flight hardware that were not per drawing, e.g. due to late fit issues or lack of adequate retention (sometimes detected just prior to launch as sagging due to gravity). Inspections/walk-downs of flight hardware that were instituted early in ISS assembly phase proved to be valuable, but the lesson was again lack of coordination with appropriate stake-holders. PTCS also advocates that the thermal team should have signature authority on thermal cover drawings, including blankets, shrouds, etc.

Three particular areas where unique data processing and temperature mapping have been required are in structural, condensation, and contamination assessments.

For contamination, comprehensive time at temperature histories may required to ensure compatibility with out-gassing test data.

For condensation, temperature mapping and history for surfaces exposed to cabin atmosphere may be required to more credibly assess condensation risk, amounts, and ventilation rates for evaporation.

For structures, temperature mesh compatibility to reflect high stress areas may need consideration. In addition, difficulties may arise when attempting to screen thermal data for identification of high thermal load cases. An improved screening method may be needed. Temperature differential requirements needed to support structural deflections may be critical, particularly in cases where the launch configuration has changed. Special attention is also needed to fidelity requirements for complex mechanism tolerances (e.g. deflection concerns in plane and out of plane) and bearing designs.

F. Modeling Nominal and Off-Nominal

PTCS experience has shown that concept of operations or design reference missions do not necessarily capture all configurations that may drive design and modeling requirements. Requirements should also address maintenance, removal and replacement (R&R) configurations, off-nominal or contingency flight trajectories or maneuvers, and higher-level system/vehicle off-nominal or contingency configurations including rotating elements, e.g. communications equipment, radiators, solar arrays. Again, PTCS advocates for a strong systems engineering presence.

While thermal models often exploit symmetry when possible, PTCS encourages explicit modeling of fault tolerance and redundancy attributes to enable discrete assessments when required as well as modeling of surface and components otherwise protected by removable thermal covers or structure.

Fluid systems may be vulnerable to shut down resulting in loss of cooling, stagnant fluid, and hydraulically locked fluid volumes.

G. Heaters

ISS has experienced numerous on-orbit failures of film heaters, where high power density (i.e. Watts per square inch) was deemed the most likely root cause, resulting in an open circuit and loss of one or more heater elements.

These types of failures have tended to occur early in operational life, often during initial heater cycling, and are most likely a result of workmanship issues leading to heater debond and burnout.

Available guidelines to limit heater power density were not strictly adhered to by ISS, typically due to design limitations, e.g. lack of available surface area at required heater locations. In addition, while qualification thermal vacuum testing was often performed to verify design, acceptance thermal vacuum testing on flight hardware, critical for workmanship screening, was not.

As a lesson-learned, a not to exceed three Watts per square inch criteria was established by ISS as a level sufficiently low to enable heaters to withstand voids in bonding without heater failure. The criteria also addresses the following: 1) perfect heater installation should not be expected, 2) acceptance thermal vacuum testing of heater installation workmanship may be cost prohibitive or not possible, 3) visual inspection is not always possible, and 4) visual inspection cannot reliably detect imperfections that may be a prelude to failure.

The following additional guidelines pertain to applications where higher power densities are required: 1) implement additional heater element heat sinks, 2) increase heater circuit power margins, and 3) ensure adequate redundancy consistent with fault-tolerance requirements.

H. Uncertainty Margin

A formal uncertainty margin approach must be baselined early in a program/project. Unfortunately, this was not the case in the ISS program. While more recent ISS projects as well as recent commercial vehicle programs have begun using versions of the Space and Missile Systems Center Standard, SMC-S-016 and maintaining an uncertainty margin approach, there have generally been no standard or common approaches, particularly for exceptions or additional tailoring due to model validation. Tailoring can be incredibly important for commercial off the shelf (COTS) applications, where use of a general uncertainty margin (e.g. 11 degrees C per SMC-S-016) may not be practical or feasible.

A perhaps obvious but also underappreciated benefit of uncertainty margin is in the event of an unexpected or unavoidable temperature limit violation during the sustaining engineering phase. The risks associated with a temperature limit violation, e.g. into the qualification temperature margin, while often not catastrophic, are usually difficult to fully assess, where had uncertainty margin been used, the likelihood of this occurrence may have been reduced or elimated.

In general, ISS verification used a somewhat standard bounding assumption approach with peer-reviews and some independent assessments. Critical to this approach was verification to full flight attitude envelopes and regimes. Further implementation of margin would have proved difficult, considering the Space Station Freedom (SSF) heritage of many systems, noting that SSF was being designed for a low inclination orbit with a maximum absolute solar beta angle of 52 degrees, versus ISS at a high inclination orbit and a maximum absolute solar beta angle of 75 degrees.

ISS has pursued some limited uncertainty margin study via sensitivity studies of critical engineering parameters over credible ranges, most often as part of an anomaly resolution effort; however, broader applications of this approach were deemed resource intensive and prohibitive. ISS was also asked to consider introduction of a formal uncertainty approach after the Space Shuttle Columbia accident. Again, cost was deemed prohibitive; however, a related aspect was implemented, which was a renewed emphasis and scrutiny in regard to the usage of models consistent with intent for which the model was developed, e.g. a specific design or requirement verification, and any inherent limitations this may impose. A standard practice for ISS is to scrutinize model usage in this manner, particularly for anomaly resolution or new applications.

ISS also had no formal thermal model validation requirement for verification of requirements by analysis. A limited model validation exercise was conducted with flight data during the early phases of ISS assembly because of some initial flight data and model reconciliation efforts. Information gathered proved useful and was rolled into existing processes and best practices.

I. Temperature Sensors

Temperature sensor definition should consider quantities and locations applicable or necessary for all operation modes, as well as non-operation modes, through the life cycle of the hardware. Note that model validation opportunities may continue to arise through the sustaining engineering phase; for example, performance trending may reveal unexpected trends due to contamination of external surfaces, power and voltage deviations, altered configurations, etc.

Temperature sensor calibration must be managed so that re-visitation can be done as needed, e.g. changes due to new cabling/wiring, relocation of hardware, and software updates.

PTCS advocates for strategic alignment of sensor locations in terms of where temperature limits apply and where test instrumentation was used in order to minimize reliance on large sensor offsets, i.e. a known delta temperature between a sensor location and area of interest. Offset is not an error and should be derived from test or analysis.

Large sensor errors can be problematic and may complicate verification and certification margin approaches, so consider testing to confirm/reduce errors.

Management of temperature sensor errors and offsets is critical to defining sensor “redlines” for the operation teams. The definition of sensor redlines should be put under configuration control.

Avoid error “double-booking”, which can occur when an operations limit and an analysis both account for sensor error. If analysis also includes the error, the definition of an operational constraint (e.g. time required to reach a temperature limit) based on the sensor reading could “double-book” the error.

J. Operations and Sustaining Engineering

Operations planning analysis, also referred to as mission, date, or event-specific analysis was critical to the ISS program during the assembly phase, and remains critical today for resupply, anomaly resolution, maintenance, science payload delivery and installation, and sustaining engineering in general. The critical importance is largely because in most instances, some facet of an operation requires hardware to be in a vulnerable state, e.g. unpowered, or in the case of a failure response, perhaps a temporary state that the hardware design was not intended.

A more pragmatic approach is advised for date-specific events or when perhaps a specific range of dates is known. However, whenever possible, a launch date-specific analysis is not recommended, as the goal should be for thermal constraints to operational plans to support the full launch window.

For ISS, the following parameters have typically been scrutinized for date or event-specific applicability: the planned ISS flight attitude and vehicle configuration, particularly the timing of configurations and including all rotating elements, e.g. radiators, solar arrays; solar beta angle range; and solar flux. There is tremendous value in the ability to limit the assumptions for possible parameter ranges which then lends much more feasibility to the definition of the possible contingency response, particularly for highly choreographed events such as for space walk or robotic timelines. In addition, the specificity allows for reduced analysis case matrices, more efficient usage of resources, and the ability to respond more quickly to operational changes while reducing schedule impacts.

Occasionally, as an event date draws near, a request for an analysis update may be deemed advantageous in order to provide further refinement of constraints to operational plans. This can be done via a mission action request (or “chit”). More infrequent, but also possible if coordinated and agreed in advance with appropriate stakeholders, a chit may be submitted immediately post launch, the advantage here being that specific calendar days (and solar beta angle range) for operational events may now be known and essentially fixed.

In regards to sustaining engineering, a related aspect to event-specific analysis is failure response, where the event is a component failure or an off-nominal configuration because of a failure. Again, a pragmatic approach is required in order to provide a timely response to support near-term plans, both safing of the vehicle as well as urgency of the next required response. Urgency is also related to the consequences of what is called the next-worst failure (NWF), particular due to a vulnerability associated with a lack/loss of redundancy. Recall that a critical question in preparation to any failure or off-nominal configuration response is whether the available thermal models are appropriate and plans are consistent with intended usage of the model.

Once the vehicle is safed and the NWF impacts are addressed, a more detailed assessment to support long-term planning can begin, where a much wider range of conditions can be fully considered.

Performance trending during the sustaining engineering phase is critical to monitoring of hardware and system health and may provide insight via unexpected signatures or trends that may be a prelude to a limit violation or perhaps a failure. Performance trending also presents a unique opportunity for additional model validation under realistic flight conditions often unattainable in test.

III. Conclusion

This paper has offered a range of real world PTCS lessons-learned with a recurring theme that thermal teams are critical stakeholders that must be engaged in the early definition phase of programs/projects, where the entire hardware life cycle must be considered in order to properly define scope and budget.

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