JPL Thermal Design Modeling Philosophy and NASA-STD-7009 Standard for Models and Simulations – A Case Study

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The Standard JPL thermal engineering practice prescribes worst-case methodologies for design. In this process, environmental and key uncertain thermal parameters (e.g., thermal blanket performance, interface conductance, optical properties) are stacked in a worst case fashion to yield the most hot- or cold-biased temperature. Thus, these simulations would represent the upper and lower bounds. This, effectively, represents JPL thermal design margin philosophy. Uncertainty in the margins and the absolute temperatures is usually estimated by sensitivity analyses and/or by comparing the worst-case results with "expected" results. Applicability of the analytical model for specific design purposes along with any temperature requirement violations are documented in peer and project design review material. In 2008, NASA released NASA-STD-7009, Standard for Models and Simulations. The scope of this standard covers the development and maintenance of models, the operation of simulations, the analysis of the results, training, recommended practices, the assessment of the Modeling and Simulation (M&S) credibility, and the reporting of the M&S results. The Mars Exploration Rover (MER) project thermal control system M&S activity was chosen as a case study determining whether JPL practice is in line with the standard and to identify areas of non-compliance. This paper summarizes the results and makes recommendations regarding the application of this standard to JPL thermal M&S practices.

Acronyms

AFT	Allowable Flight Temperature
CAIB	Columbia Accident Investigation Board
CAS	Credibility Assessment Scale
CDR	Critical Design Review
CM	Configuration Management
COTS	Commercial-Off-The-Shelf
EDL	Entry, Descent, and Landing
FA	Flight Acceptance
FR	Failure Report
FS	Flight System
H/W	Hardware
ICD	Interface Control Document
M&S	Models and Simulations
MEL	Mass Equipment List
PDR	Preliminary Design Review
PEL	Power Equipment List
QUAL	Qualification
S/C	Spacecraft
TRR	Test Readiness Review
V&V	Verification and Validation

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I. Introduction

The NASA standard for models and simulations was implemented as a result of the Columbia Accident Investigation Board (CAIB) report released in 2004. In 2008, NASA released NASA-STD-7009, Standard for Models and Simulations. The scope of this standard covers the development and maintenance of models, the operation of simulations, the analysis of the results, training, recommended practices, the assessment of the Modeling and Simulation (M&S) credibility, and the reporting of the M&S results. The ultimate objective was to specify a standard method to assess the credibility of the models and simulations presented to the decision maker when making critical decisions (i.e., decisions that affect human safety or mission success) using results from models and simulations.[1] The standard development process included a study that was conducted in 2006 that provided some data regarding differences between existing practices and the new requirements proposed in the interim standard. JPL participated in the study and used the Mars Exploration Rover (MER) Cruise Stage thermal design activity as JPL's test case. Since the 2006 test case, the interim standard was updated and released. The implementation of the NASA M&S standard on projects has continued to be stalled by the perception that complying with the standard would result in significant cost increases. In addition, it is not clear that the decision makers are adequately familiar with the credibility assessment scale (CAS) to make effective use of it. This paper updates the MER test case with the released version of the standard and makes recommendations regarding the application of this standard to JPL thermal M&S practices.

II. JPL Thermal M&S Methodology

The standard JPL thermal engineering practice prescribes worst-case methodologies for design. In this process, environmental and key uncertain thermal parameters (e.g., thermal blanket performance, interface conductance, optical properties) are stacked in a worst case fashion to yield the most hot- or cold-biased temperature. These simulations represent the upper and lower bounds. This, effectively, represents JPL thermal design margin philosophy. This approach is captured in JPL's thermal design procedure.[2] Uncertainty in the margins and the absolute temperatures is usually estimated by sensitivity analyses and/or by comparing the worst-case results with "expected" results. The credibility of the model & simulation results, in JPL's case is assessed by comparing the margin from worst case Hot/Cold predicted temperature range to the Allowable Flight Temperature (AFT range) and that of the hardware test history (FA and QUAL). There are a series of credibility checks performed, such as, energy balances, heat flow diagrams, and development test data but when it comes to communicating results to the decision makers, the temperature comparison is what they understand most. These sanity checks are captured in JPL's best practices as well as available handbooks.[3-6] Details and assumptions of the analytical model being used for design purposes along with any temperature requirement violations are documented in peer and project design review material. The JPL thermal design and test margin philosophy is summarized in Figure 1.[7,8]

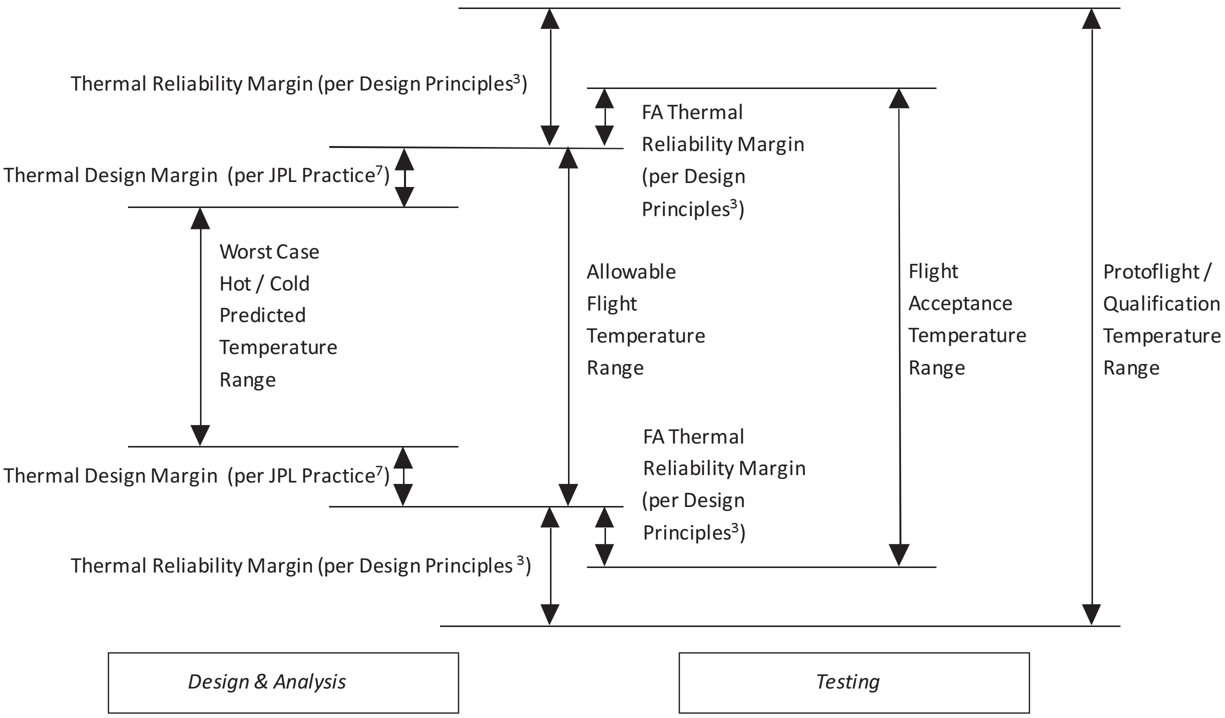

Figure 1 - JPL's Current Thermal Design Requirements

In the JPL context, robotic missions, the critical decisions have to do with human and flight hardware safety during ground and launch operations and the safety of the robotic asset through completion of the mission's scientific objectives. In many cases, it is the credibility of the engineer that communicates the M&S results and not necessarily of the results themselves that convince the decision makers. This is clearly too subjective and a more objective process should be used to ensure appropriate communication to the decision makers.

III. Mars Exploration Rover (MER) Cruise Stage Thermal M&S Activity Overview

A. NASA-STD-7009 Overview

In summary, the NASA standard specifies requirements for M&S programmatic, models, simulations and analyses, verification, validation, and uncertainty quantification, identification and use of recommended practices, training, assessing the credibility of M&S results, and reporting results to decision makers. This section will describe the MER CS M&S activity.

B. Mission Architecture

The MER flight system design adapted many successful features of the Mars Pathfinder (MPF) spacecraft design that was launched in 1996 and landed on Mars on July 4, 1997. During cruise, MER was a spin-stabilized spacecraft with a nominal spin rate of 2 revolutions per minute (rpm). The MER flight system consists of four major components: cruise stage (CS), entry, descent, and landing (EDL) system, Lander structure, and the Rover (see Figure 1). The mass allocation for the entire flight system (including propellant load) was 1065 kg.

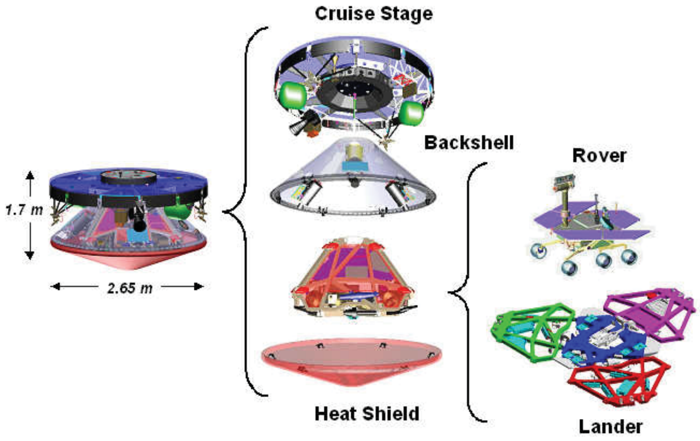

Figure 2 - MER Flight System Configuration

The two Mars Exploration Rover missions were designated as MER-A (Spirit) and MER-B (Opportunity). The first spacecraft (MER-A) was launched on June 10, 2003 atop a Boeing Delta II 7925 launch vehicle from Kennedy Space Center (KSC). The second spacecraft was launched on July 8, 2003 on a Boeing Delta II 7925H. Approximately 7 months after launch, the two spacecraft entered the Martian atmosphere directly from their interplanetary trajectories. Similar to the MPF mission, the MER entry trajectory followed an unguided, ballistic descent. The spacecraft relied on a heatshield and parachute to slow its descent through the Martian atmosphere, fired retro-rockets to reduce its vertical landing velocity, and finally deployed airbags to cushion its impact with the surface. Once several landed operations were completed, the Rovers drove away from the lander.

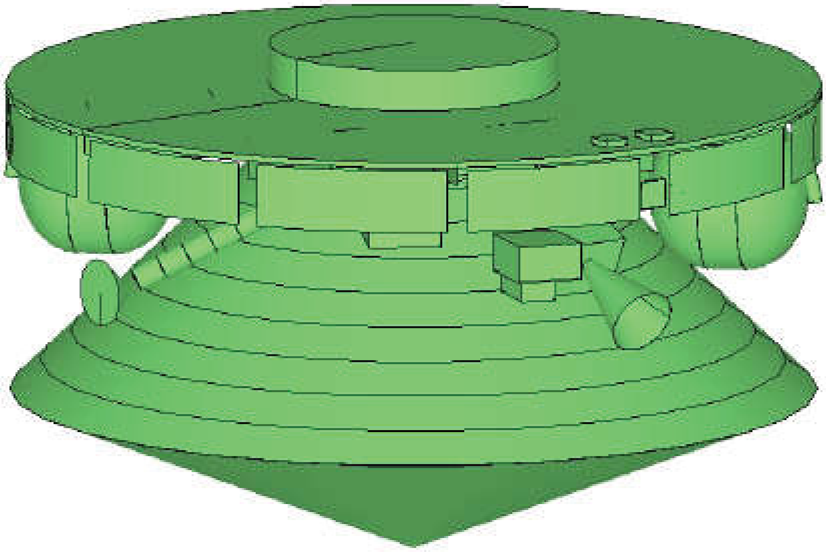

Figure 3 - MER CS GMM

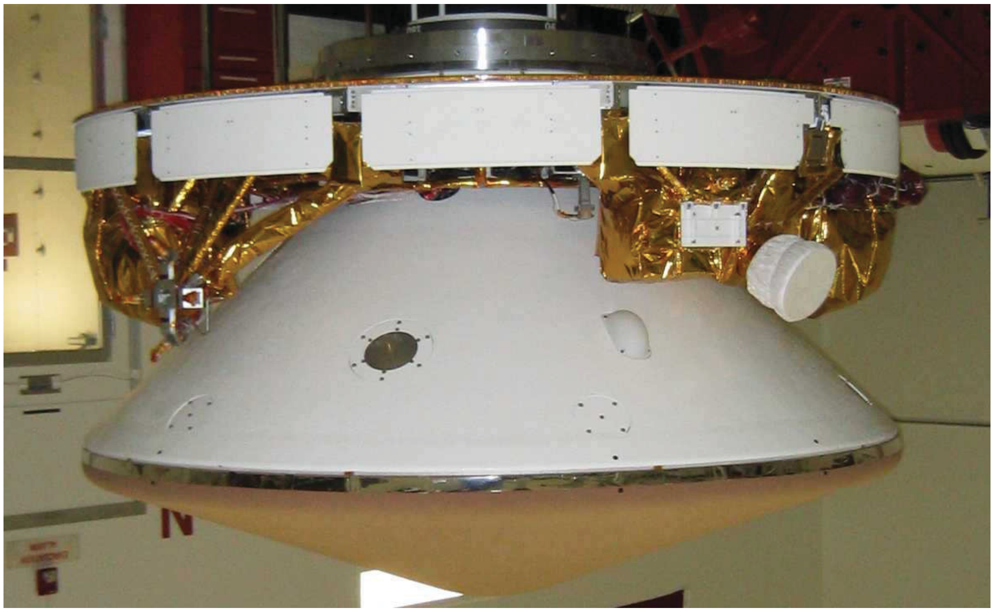

Figure 4 – MER CS Flight System for Comparison with GMM

C. Cruise Thermal Design Description

During the relatively quiescent flight from Earth to Mars, the cruise stage provided attitude control, propulsion, and power generation. The Rover, buried in the entry vehicle, provided flight computer processing and telecommunication functions. The cornerstone of the cruise thermal design was the Heat Rejection System (HRS). This was a single-phase, mechanically pumped fluid loop. The redundant integrated pump assembly (IPA), located on the cruise stage, circulated the working fluid, CFC-11, throughout the cruise stage, lander, and Rover. The primary cruise heat sources were the telecommunications hardware, 6 radioisotope heat units (RHUs) on the battery, and the electronics located within the Rover warm electronics box (WEB). The fluid loop shuttled the Rover waste heat to radiators located on the periphery of the cruise stage. The design and performance of this system has been well documented.[9,10]

To address lessons learned on MPF[11], the thermal design for the cruise stage propellant lines used the following upgraded features from the MPF design: 1) flight software controlled heaters, rather than mechanical bimetallic thermostats; 2) 8 distinct thermal regions, instead of 4; and 3) locating of line heaters at high heat loss areas (i.e., propellant line mounting supports), rather than a uniform heater power density over a control zone. Each control zone had two heaters for single point failure tolerance. The flight software enabled all 16 heaters, and staggered set-points were employed for the two heaters in a given zone to prevent simultaneous operation.

Heaters that were controlled by bimetallic thermostats were used throughout the flight system as required on the remaining hardware. Specific thermal finishes on the sun sensors, cruise solar array structure, and HRS radiators were used to maintain allowable flight temperature ranges. In the case of the cruise electronics module (CEM), it required a white radiator to contend with its relatively wide operational power variation. Thermal blanketing was conformally applied to much of the cruise stage hardware. A single-layer thermal blanket was applied to the heat shield to minimize lander heat loss.

D. MER CS Analytical Thermal Model Description

For most JPL thermal analysis, there are two components that comprised the MER CS thermal model: 1) geometric math model for the determination of radiation couplings and environmental heating, and 2) thermal math model for the determination of temperatures. In both instances, third-party commercially available software was used. The GMM (see Figure 3) and TMM were developed with the Thermal Synthesizer System from Spacedesign. For comparison, the CS flight system is shown in Figure 4. The TMM solver within Thermal Synthesizer System is essentially the SINDA/FLUINT software and graphical results are shown in Figure 5.[12] For comparison, the flight hardware is shown in Figure 6.

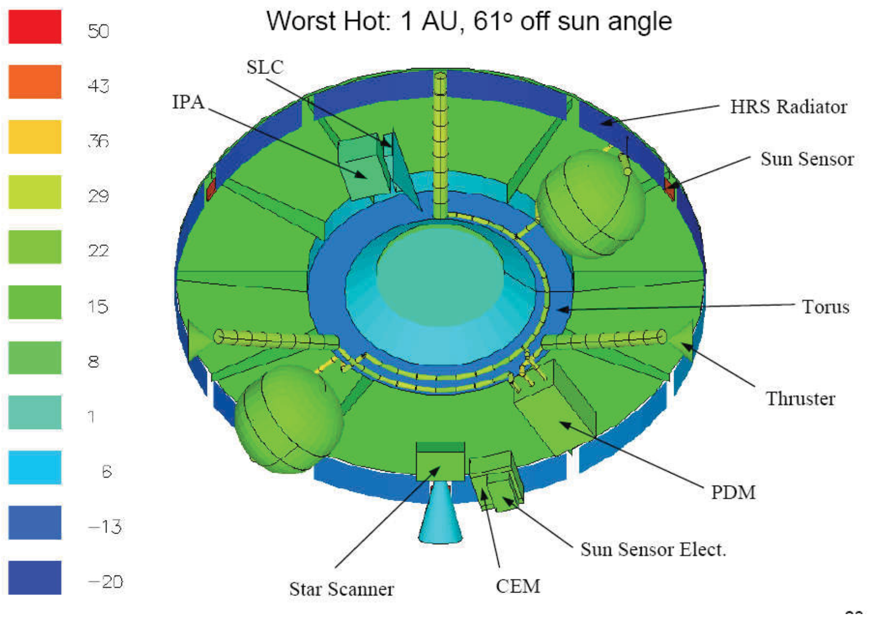

Figure 5 – MER CS Model & Simulation Results

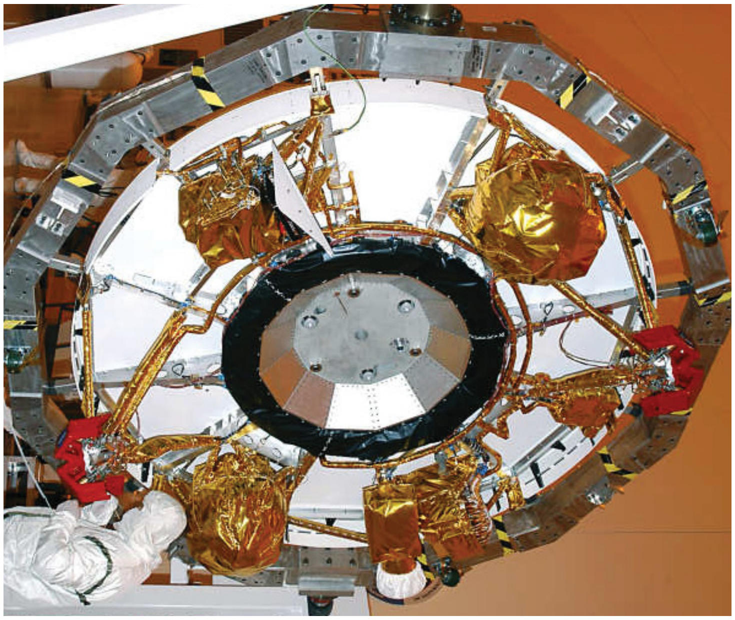

Figure 6 – MER CS Flight System for Comparison with Model

IV. Comparison to NASA-STD-7009 Requirements

This section will compare the MER CS M&S activities with NASA-STD-7009 M&S Standard Section 4 requirements. The compliance matrix was completed with the author's assessment of compliance, at some level, along with the type of existing evidence. The rollup score was not attempted.

A. Programmatics

The most visible product is the M&S plan. The plan must anticipate the critical decisions that may impact human and flight hardware safety. Portions of the plan that require the most planning and thought are Verification, Validation, and Uncertainty Quantification, Configuration Management, and the definition of the Waiver Process. Establishing such a plan would specify the sufficiency thresholds that would enable CAS assessment throughout the development lifecycle. The MER CS analysis effort, and indeed all thermal design efforts to date, lacked such a plan. If such a plan existed, there would be explicit decisions, based on M&S, associated with ground operations, where the use of CFC-11 is hazardous to humans and our environment. M&S was required to understand the risk associated with using CFC-11 in ground operations and in flight, where a failure of the HRS system would result in loss of mission.

B. Models

For flagship missions such as Voyager, Galileo, and Cassini, JPL thermal engineering practices were generally consistent with the intent of the M&S Standard. The largest challenge has been the documentation. Previous flagship missions had much longer development lifecycles and as such, focused more on careful documentation. MPF was a technology demonstration mission so its documentation was on a best effort basis. Although the lifecycle for MER was much shorter than the previous flagship missions, the intent was to provide a similar level of documentation for the CS model but this was descoped as more pressing issues diverted funding and attention.

C. Simulations and Analyses

Most of the M&S Standards were captured for JPL flagship missions. However, again, this was not the case for the MER CS due to intense schedule pressure. The cost associated with compliance is deemed to be incremental since the model documentation cost impact covers most of these items from a MER CS analytical thermal model standpoint.

D. Verification, Validation, Uncertainty Quantification

Much of the flight project thermal analyses are conducted with accepted commercially available tools (e.g., SINDA, TSS, Thermal Desktop, I-DEAS/TMG, NX Space System Thermal). Each of these vendors has undergone rigorous verification testing with standard closed-form solutions. The tool user is obligated to perform verification checks on the constructed model, and this was indeed the case for MER. The documentation of the verification was elementary and mostly contained in PDR and CDR presentations, thus it lacked the documentation rigor of the M&S Standards. Given its heritage to MPF, MER CS analysis results were cross-checked against MPF flight data for applicable conditions. For the MER CS, mostly worse-case analyses were performed and were supplemented by temperature sensitivity analysis for modest allowable flight temperature limit violations. In addition, once system-level testing was completed, the analytical MER CS model was validated by correlation to empirical data. The validation documentation was performed. Where the MER CS was lacking involved the completeness of documentation.

E. Assessing the Credibility of M&S Results

The Credibility Assessment Levels, as defined in NASA-STD-7009, are described in Table 1 below.

Level	Verification	Validation	Input Pedigree	Results Uncertainty	Results Robustness	Use History	M&S Management	People Qualifications
4	Numerical errors small for all important features.	Results agree with real-world data.	Input data agree with real-world data.	Non-deterministic & numerical analysis.	Sensitivity known for most parameters; key sensitivities identified.	De facto standard.	Continual process improvement.	Extensive experience in and use of recommended practices for this particular M&S.

Level	**Verification**	**Validation**	**Input Pedigree**	**Results Uncertainty**	**Results Robustness**	**Use History**	**M&S Management**	**People Qualifications**
3	Formal numerical error estimation.	Results agree with experimental data for problems of interest.	Input data agree with experimental data for problems of interest.	Non-deterministic analysis.	Sensitivity known for many parameters.	Previous predictions were later validated by mission data.	Predictable process.	Advanced degree or extensive M&S experience, and recommended practice knowledge.
2	Unit and regression testing of key features.	Results agree with experimental data or other M&S on unit problems.	Input data traceable to formal documentation.	Deterministic analysis or expert opinion.	Sensitivity known for a few parameters.	Used before for critical decisions.	Established process.	Formal M&S training and experience, and recommended practice training.
1	Conceptual and mathematical models verified.	Conceptual and mathematical models agree with simple referents.	Input data traceable to informal documentation.	Qualitative estimates.	Qualitative estimates.	Passes simple tests.	Managed process.	Engineering or science degree.
0	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidences.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.
	M&S Development		**M&S Operations**			**Supporting Evidence**		

Table 1 – Key aspects of Criticality Assessment Levels

1. M&S Development

Verification

JPL has established a formal process for Verification and Validation (V&V).[13] The thermal engineering area has instantiated this institutional process and developed a Thermal System V&V process.[14] For the purposes of analytical thermal models, the concept of solution verification would serve a means for assessing the accuracy of the nodalization. Lumped parameter solution methods specify convergence criteria based on energy balance and number of iterations. However, the granularity of the nodalization is a judgment call, and the guiding principle is the notion that a node represents an isothermal volume. Since the nodalization is made a priori, the validation of this assumption must be made after the analysis is completed. For PDR-level analysis, this type of model “shakedown” should be performed as a best practice, and then the model pedigree can be pushed forward into the detailed model phase. However, with recent schedule pressures, this practice has been diminished.

In the case of the MER CS model, the symmetric configuration and the spinning nature of the flight system significantly mitigated the need to conduct solution verification. In addition, Level 2 compliance was achieved by comparing temperature results with the heritage MPF analysis. If Level 3 compliance were required, iterative analysis addressing the nodalization would be required. This would be a time-consuming undertaking due to the process of re-nodalization and recalculation of radiation coupling, environmental heating, and temperatures, resulting in a cost increase.

Validation

A system-level thermal balance test is the only opportunity the thermal engineer has to empirically validate the spacecraft thermal design. Ideally, this test would be conducted in a facility which could perfectly simulate the thermal conditions on orbit (e.g. solar intensity, solar spectrum, solar collimation, thermal influence of the earth, etc.) If such a test could be conducted with a complete flight spacecraft, and all the physical configurations, all the in-flight solar orientations and all the planned internal power states could be addressed by thermal balance test cases, there would be no need for an analytical model of the spacecraft. The data from the test could be re-labeled “flight predicts”.

Current test reality, however, requires that an analytical model be developed that can address the actual test environment and its influence on the flight spacecraft system thermal behavior. So the model must consist of the flight spacecraft model in whatever configuration it’s to be tested, placed within a model of the in-chamber surroundings (shrouds, support structures, MGSE, etc.)

2. M&S Operations

Input Pedigree

The input pedigree is assured in various forms over the course of the development lifecycle. Initially, the key inputs and parameters are governed by documented best practices and handbooks (Ref. 2-8) and systems engineering tools, Mass Equipment List (MEL) and Power Equipment List (PEL), are project level configuration management documents that track system level resources. These documents start off by tracking current best estimates (CBE) against system level allocations. Once the subsystem flight hardware has been built and measured, the MEL and PEL are updated with actual as measured values. Other inputs, such as conductivity as a function of temperature, had associated documentation to verify their origin. These include specification sheets, handbook references, and/or development and characterization test data. The environmental inputs are usually captured in an Environmental Requirements Document that will typically attempt to bound the anticipated environments.

Results Uncertainty

Uncertainty is usually estimated by sensitivity analyses and/or by comparing the worst-case results with "expected" results. The standard calls for a more rigorous mathematical treatment. In order to meet Level 3, a new JPL practice for determination temperature probability distributions for the MER CS model would need to be developed and a significant cost increase could be expected.

Results Robustness

Robustness is again, usually estimated by sensitivity analyses as discussed above and the margins against requirements. The sensitivity analyses are performed on what the engineer considers as the key parameters. This may not meet the strict standard requirement. Robustness is typically assessed by peer and project review boards.

3. Supporting Evidence

Use History

Third-party commercially available software tools are used for the determination thermal radiation coupling, environmental heating, and resulting temperatures. These tools have been rigorously tested and have been widely accepted for use by NASA Centers. These vendors hold the responsibility for coding and solution verification. Applicability of analytical model for specific design purposes along with any temperature requirement violations are documented, usually, in PDR and/or CDR peer review material. The assessment of JPL current practices would yield between Level 2 and 3 on the CAS. The MER CS thermal analysis, as a minimum, would meet CAS Level 2. The areas that would rate Level 3 for this analysis include: Code Verification (vendor controlled configuration management process), Validation (since the model was correlated to a series of empirical test cases), and Level of Technical Review (formal internal peer review conducted).

M&S Management

The local JPL thermal system engineering and design procedure and thermal operations procedure provide a general list of documentation products including the preliminary and detailed peer review packages. However, there is no further detail regarding required content. While there is some general intent, JPL institutional processes lack the specific definition that the M&S Standards provide. The most visible deficiency is the lack of formal configuration management of the models and their results (simulations, etc.).

People Qualification

The MER CS analytical model that was developed for design was "operated" by a single engineer with the intent to consolidate the model for mission operations purposes. The training for the thermal engineer performing and M&S activity is captured in our institutional training profiles.[15] The training for mission operations purposes is captured in our institutional procedures.[16] The M&S Standards were not strictly followed. The model had a number of "self documenting" features such as embedded comments to specify required input, and these features would be insufficient as far as the M&S Standard is concerned. However, a user's guide was developed and used for mission operations training. Recognition of incredulous results was based on engineering experience (including first principles hand calculations) rather than exacting criteria. A configuration management plan was lacking even though the model was exercised by one engineer. The understanding of this M&S Standard is analogous to obtaining the mind-set for flight hardware delivery. There is rigor in the process of developing, implementing, and maintaining models and simulation. The amount of effort to attain Level 3 (extensive training and experience related to the M&S activity) is highly speculative but an estimate on the MER CS M&S activities is attempted below.

F. Reporting to Decision Makers

The MER CS M&S was reported formally to Project and Technical Line Management and the extent of its compliance with the NASA-STD-7009 is shown in Table 2.

Requirements	Compliance Status (C, NC, N/A)	Method	Evidence
Req. 4.1.1 -Shall document the risk assessment for any M&S used in critical decisions.	NC		
Req. 4.1.2 -Shall identify and document those M&S that are in scope.	NC		
Req. 4.1.3 -Shall define the objectives and requirements for M&S products including the following:	NC		
a. The acceptance criteria for M&S products, including any endorsement for the M&S.			
b. The rationale for the weights used for the subfactors in the Credibility Assessment Scale (see Appendix B.4).			
c. Intended use.			
d. Metrics (programmatic and technical).			
e. Verification, validation, and uncertainty quantification (see section 4.4.)			
f. Reporting of M&S information for critical decisions (see section 4.8).			
g. CM (artifacts, timeframe, processes) of M&S.			
Req. 4.1.4 -Shall develop a plan (including identifying the responsible organization(s)) for the acquisition, development, operation, maintenance, and/or retirement of the M&S.	NC		
Req. 4.1.5 -Shall document any technical reviews performed in the areas of Verification, Validation, Input Pedigree, Results Uncertainty, and Results Robustness (see Appendix B).	C	PDRs, CDRs	Document
Req. 4.1.6 -Shall document M&S waiver processes.	NC		
Req. 4.1.7 -Shall document the extent to which an M&S effort exhibits the characteristics of work product management, process definition, process measurement, process control, process change, and continuous improvement, including CM and M&S support and maintenance.	NC		
Req. 4.2.1 -Shall document the assumptions and abstractions underlying the conceptual model, including their rationales.	C	PDRs, CDRs	Document
Req. 4.2.2 -Shall document the basic structure and mathematics of the model (e.g., reality modeled, equations solved, behaviors modeled, conceptual models).	C	PDRs, CDRs	Document
Req. 4.2.3 -Shall document data sets and any supporting software used in model development and input preparation.	C	PDRs, CDRs	Document
Req. 4.2.4 -Shall document required units and vector coordinate frames (where applicable) for all input/output variables in the M&S.	C	PDRs, CDRs	Document
Req. 4.2.5 -Shall document the limits of operation of models.	NC		
Req. 4.2.6 -Shall document any methods of uncertainty quantification and the uncertainty in any data used to develop the model or incorporated into the model.	NC		
Req. 4.2.7 -Shall document guidance on proper use of the model.	NC		
Req. 4.2.8 -Shall document any parameter calibrations and the domain of calibration.	C	PDRs, CDRs	
Req. 4.2.9 -Shall document updates of models (e.g., solution adjustment, change of parameters, calibration, and test cases) and assign unique version identifier, description, and the justification for the updates.	C	Internal Memoradums	Document
Req. 4.2.10 -Shall document obsolescence criteria and obsolescence date of the model.	NC		
Req. 4.2.11 -Shall provide a feedback mechanism for users to report unusual results to model developers or maintainers.	NC		
Req. 4.2.12 -Shall maintain (conceptual, mathematical, and computational) models and associated documentation in a controlled CM system.	NC		
Req. 4.2.13 -Shall maintain the data sets and supporting software referenced in Req. 4.2.3 and the associated documentation in a controlled CM system.	NC		
Req. 4.3.1 -Shall do either of the following:	NC		
a. Ensure that simulations are conducted within the limits of operation of the models, or			
b. Placard the simulation and analysis results with a warning that the simulation may have been conducted outside the limits of operation and include the type of limit that may have been exceeded, the extent that the limit might have been exceeded, and an assessment of the consequences of this action on the M&S results.			
Reg. 4.3.2 -Shall document and explain any observed warning and error messages resulting from the execution of the computational model.	NC		
Reg. 4.3.3 -Shall document which computational models were used (including revision numbers) in the simulation.	C	PDRs, CDRs	Document
Reg. 4.3.4 -Shall document the versions of M&S results.	C	PDRs, CDRs	Document
Reg. 4.3.5 -Shall document data used as input to the simulation, including its pedigree (see Appendix B).	C	PDRs, CDRs, MELs, PELs	Document
Reg. 4.3.6 -Shall document any unique computational reguirements (e.g., support software, main memory, disk capacities, processor, and compilation options).	C	PDRs, CDRs	Document

Table 2 - NASA-STD-7009 Compliance Matrix for MER CS

G. M&S Cost Impact/Benefits

The cost impacts of implementing the standard for the MER CS M&S activity will be presented as a percentage delta from the total actual cost. This assessment of each standard element (e.g., programmatic requirements, models, simulations and analyses, etc.) could be assessed looking across the entire MER lifecycle. It is understood that this is only one data point and that this M&S activity may represent a less complex activity. The MER Rover (Surface System), JWST, and ARES-1, for example, are much more complex M&S activities. In the case of the MER CS modeling and simulation, approximately 15% of additional funding would have been required to bring the modeling and simulation effort into Level 3 compliance. The cost impact summary is shown in Table 3.

	NASA-STD-7009	
		% Increase
4.1	Programmatic Requirements	2%
4.2	Models	2%
4.3	Simulations and Analyses	1%
4.4	Verification and Validation	1%
4.5	Uncertainty Quantification	2%
4.6	Training	2%
4.7	Assessing the Credibility of Models & Simulations Results	3%
4.8	Reporting Results to Decision Makers	2%
	% of Actual MER CS M&S Cost	**15%**

Table 3 - Cost Differential (%) from Baseline to Achieve Compliance

V. General Observations

A. MER CS Thermal Model Summary

The primary objective of this case study involved the determination if the use of the M&S Standards would produce a more credible product when presented to the decision makers. Level 2 credibility exists with current practices, and some credibility categories were Level 3 compliant. Thus, the current JPL practices would only require a relatively small change in behavior to be entirely Level 3 conforming. Documentation remains the single greatest challenge. Projects initially are well-intended to meet documentation requirements and then schedule and cost pressures in Phases C and D result in significant descoping or total elimination. As an institution, JPL projects will be challenged to commit to the appropriate credibility level and hold to this commitment throughout the project lifecycle.

The main spirit of the M&S Standards must be understood and retained as an underlying theme. All standards encounter complex situations where sound and prudent judgment should be exercised instead of literal application without question. JPL line management may view this standard as a path toward achieving technical excellence. JPL project management may view this as a hindrance to cost and schedule control. History will serve as the metric regarding the utility of this standard, and JPL should use a mediated and balanced approach to extract the maximum benefit of this standard.

B. Usability of the Standard and Scales

The thermal analysis arena is unique due to its reliance on third party analytical solvers. This has been the case for over 40 years. Hence, the responsibility for code verification and parts of solution verification has fallen on the commercial vendors. When new vendors enter the thermal analysis arena, they usually demonstrate the technical rigor of their tools. If this responsibility were shifted or shared by users such as JPL then the application of the M&S Standards would present a significant interference in our current thermal analysis practice.

C. Usefulness of the Standard and Scales

The standard attempts to ensure that the credibility of the results from models and simulations is properly conveyed to those making critical decisions. During JPL in-house flagship missions such as Voyager, Galileo, and Cassini, the rigor of modeling and simulation results were fairly well aligned with the primary objective of the M&S Standards. During the era of Faster, Better, and Cheaper, this rigor was nearly abandoned. After the MCO and MPL failures, JPL made strides to improve its modeling and simulation process. MER was a step in the right direction. There was fairly good compliance with Level 2 credibility, although, general documentation requirements were not met. If implemented by JPL Projects without exception, these M&S Standards will meet the primary objective of providing contextual modeling and simulation information for the rendering of important decisions. Consequently, the resultant modeling and simulation product will be improved. In the high schedule pressure environment where much of JPL flight project work is performed, critical modeling and simulation information is easily omitted from communications. This standard will ensure the contextual modeling information is made available to those making critical decision, and will also serve as historical archives for future projects that face similar situations and/or claim heritage to past projects.

In addition, this Standard provides assurance that the results have the necessary credibility to assess technical performance versus functional requirements. This is usually performed during the review process at JPL, be it peer or Project-level. Again, the M&S Standards would provide an easy and readily comprehensible means of conveying the analysis credibility. In addition, a review board can probe into any of the credibility categories to more methodically understand the analysis.

Modeling and simulation standards becomes increasingly important and urgent as space systems become more and more complex and do not lend themselves to ground testing. Thus, reliance upon analysis as the validation method becomes of paramount importance. In addition, uncovering design deficiencies by test occurs late in the product lifecycle and thus, more costly and arguably riskier to rectify. More rigorous modeling and simulation would avoid such development pitfalls, and this standard can be an effective and proactive design tool.

The standard does acknowledge that ***ALL*** its requirements may not be applicable to ***ALL*** projects and is currently not mandated. The standard ***encourages*** programs and projects to apply it if the M&S results may impact future critical decisions.

VI. Development of a Discipline Specific Handbook

The overarching objectives of the standard are needed in the current era of large space vehicles that rely on models and simulations for V&V (e.g. JWST and ARES-1). The standard recommends discipline specific handbooks be developed. A discipline specific handbook is appropriate for the thermal discipline and should be implemented in a way that simplifies the Thermal M&S CAS communication of all of NASA's programs and projects. While many of the requirements specified in the standard are reasonable, they rely on the engineer's best practices and this varies among the agency's thermal engineering community. Configuration management of models and the simulation results is critical for project/program development robustness as well as reuse of M&S and training of the new generation of engineers.

VII. Conclusions

The typical response that "we've always done it this way" is not acceptable in the post CAIB era. The JPL process is similar to agency wide thermal processes but these lack configuration management and often rely on the individual engineer to document their work. The return on investment with a standard and handbook would be significant with improved critical decision making input and a better design verification and validation process to assure that functional requirements are met through modeling and simulation. Whether a project should embark on Level 3 credibility will strongly depend on the cost of mission failure. JPL flagship missions are clearly high visibility projects whereas small instruments may be more risk-friendly. In the current era of constrained discretionary federal spending, tight project budgets force engineers to be less rigorous in their M&S CM and analysis documentation. The M&S results must be auditable. A model in its current form is not easily penetrable for review purposes. While the magnitude of the cost impact is significant, it is within the required JPL cost reserves. In the case of the thermal design domain, as the M&S Standards become ingrained, this cost increase will begin to become inconsequential.

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