

LOFTID Aeroshell Thermal Response Uncertainty Analysis Utilizing the End-to-End Monte Carlo Approach

Steven Andrew Tobin¹, Andrew Joseph Brune², Angela L. Bowes³
NASA Langley Research Center, Hampton, VA 23681, USA

A probabilistic thermal margin process has been performed to design the flexible thermal protection system (FTPS) and select entry trajectory constraints given an acceptable risk level for the Low-Earth Orbit Flight Test of and Inflatable Decelerator (LOFTID) project. Uncertainties exist in atmospheric entry aeroheating environments and the predicted thermal response of thermal protection system (TPS) material. Entry vehicle TPS is often over-sized to mitigate uncertainty by combining conservative bounding scenarios together. The probabilistic thermal margin process allows engineers to make informed aeroshell design, flight design, and FTPS performance risk trades while preventing excessive FTPS margin from being applied. This paper describes the uncertainty analysis methodology used to carry out a probabilistic thermal margin process used for LOFTID's aeroshell and explains how the calculated probability of exceeding flight allowable temperatures is used to design the FTPS and establish nominal flight design constraints. This probabilistic thermal margin process had never been applied to entry, decent, and landing design for a flown entry vehicle and it is one of the LOFTID project's goals to demonstrate its merits.

Nomenclature

T_{Exp}	=	Expected (mean) Maximum Temperature
T_{Allow}	=	Flight Allowable Maximum Temperature
$T_{97.7_Calc}$	=	Calculated 97.7 Percentile Maximum Temperature
T_{Limit}	=	Inflatable Structure Material Failure Temperature Limit
T_{Safe}	=	Temperature Limit Safety Knock Down
C_H	=	Enthalpy-Based Convective Heat Transfer Coefficient
q_{rad}	=	Radiative Heat Flux
ρ_∞	=	Freestream Density
V_∞	=	Atmosphere Relative Freestream Velocity
k_{CH}	=	Enthalpy-Based Convective Heat Transfer Coefficient Multiplier Factor
k_{rad}	=	Radiative Heat Flux Multiplier Factor
q_{net}	=	Net Surface Heat Flux
H_{0e}	=	Total Enthalpy
H_w	=	Wall Enthalpy
ϵ	=	FTPS Outer Fabric Surface Emissivity
σ	=	Stefan Boltzmann Constant
T_w	=	Wall Temperature
T_b	=	RSS Baseline FTPS Insulation Thickness
T_F	=	RSS Final FTPS Insulation Thickness
T_1	=	RSS Case 1 FTPS Insulation Thickness
T_2	=	RSS Case 2 FTPS Insulation Thickness
T_3	=	RSS Case 3 FTPS Insulation Thickness

¹ Aerospace Engineer, LOFTID Thermal Lead, Structural and Thermal Systems Branch.

² Aerospace Engineer, LOFTID Uncertainty Quantification Lead, Structural and Thermal Systems Branch, AIAA Senior Member.

³ Aerospace Engineer, LOFTID Flight Mechanics Lead, Atmospheric Flight and Entry Systems Branch, AIAA Senior Member.

I. Introduction

Potential entry, decent, and landing (EDL) missions have been identified that will require an entry system to have an aeroshell much larger in diameter than the diameter of any current feasible launch vehicle [1]. These missions include high-altitude landings on Mars and landing high mass payloads on Earth and other planets or moons with an atmosphere. NASA has been developing the Hypersonic Inflatable Aerodynamic Decelerator (HIAD) to use as a potential entry system for these applications. An inflatable heatshield can be packed and stowed to fit within current launch vehicle shroud sizes and then deployed (inflated) prior to atmospheric entry resulting in a heatshield much larger than the stowed diameter, providing increased mission capability in terms of drag generation. This allows for increased flexibility in landing location or additional payload capability. Due to the high heat loads encountered in hypersonic atmospheric entry environments, the inflatable aeroshell of a HIAD entry system relies on a layered blanket flexible thermal protection system (FTPS) to prevent the underlying stacked toroid inflatable structure (IS) from exceeding its thermal limits. Figure 1 depicts the Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) HIAD reentry vehicle.

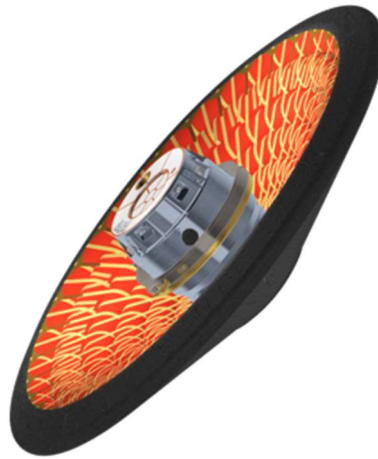


Fig. 1 LOFTID Experimental HIAD Reentry Vehicle

FTPS materials and layups have undergone extensive aerothermal arc-jet testing in a stagnation configuration to evaluate thermal performance and provide boundary condition and in-depth temperature measurement data for thermal model correlation and validation [1]. The general FTPS material layup is shown in Figure 2, which displays numbered interfaces between the layers. The outer fabric protects the underlying insulation layers from being directly exposed to the incident convective heat flux and the aerodynamic shear forces. The outer fabric also protects the underlying insulation layers from the abrasion and mechanical forces associated with packing and deploying. The insulator layers reduce thermal soak back and the gas barrier prevents hot gas impingement on to the underlying IS.



Fig. 2 General FTPS Layup

The LOFTID is a demonstration flight project that will be used to validate computational models and advance understanding of the HIAD technology. Entry vehicle heat shields are typically over-sized for the heat loads that are experienced during atmospheric entry by designing them to survive combined conservatively bounding scenarios. Since the LOFTID project is an experimental flight demonstration, it is desired to drive the FTPS and IS to temperatures that cover a large domain of applicability for the thermal response models. This will allow the thermal response models to be better improved and validated post-flight using LOFTID’s extensive instrumentation embedded within the aeroshell. Additionally, the conventional heat-shield design and margin process offers very little insight into the risk of over-temperature during flight and the corresponding reliability of the heat shield performance [2]. The probabilistic margin process has been performed to design the FTPS and entry heating constraints given an acceptable risk level for the LOFTID flight project. For a given FTPS composition, the thickness is coarsely tailored, and then entry heat load is more finely tailored so that the resulting aeroshell thermal response meets project reliability standards while allowing the FTPS and the underlying inflatable structure (IS) to be pushed to adequately high temperatures. This margin process also allows engineers to make informed aeroshell design, entry-trajectory alterations, and risk trades.

This paper describes the uncertainty analysis methodology used to carry out a probabilistic thermal margin process for LOFTID’s aeroshell and explains how the calculated probability of exceeding flight allowable temperatures is used to design the FTPS and establish nominal flight design constraints. Uncertainty analysis is carried out using an end-to-end Monte Carlo process where three separate Monte Carlo simulations are sequentially run. The first Monte Carlo simulation operates on the entry trajectory model to generate trajectory parameter dispersions that are fed into the second Monte Carlo simulation. The second Monte Carlo simulation operates on the aerothermodynamics model to generate aeroheating parameter dispersions that are fed into the third Monte Carlo simulation. The third Monte Carlo simulation operates on the FTPS material thermal response model to generate the final FTPS/IS thermal response dispersions. The end-to-end Monte Carlo simulation propagates the uncertainties of each model into the next to quantify the resulting cumulative uncertainty of the FTPS/IS thermal response. The fractional contributions of the uncertain parameters in the trajectory, aerothermal, and thermal response models to the variance in the FTPS/IS thermal response is determined as a byproduct of the Monte Carlo analysis discussed in Section IV.C. The “structural uncertainty” of the FTPS thermal response model is evaluated by flight relevant arc-jet ground testing and model error analysis using test measurements. This probabilistic thermal margin process had never been applied to an EDL design for a flown entry vehicle, and it is one of the LOFTID project’s goals to demonstrate its merits.

II. Aeroshell Thermal Response and Margin Process

This section provides an overview and objectives of the probabilistic FTPS/IS thermal margin process.

A. Aeroshell Thermal Response Analysis Overview

The LOFTID reentry vehicle (RV) FTPS protects the aeroshell IS from over-heating during atmospheric entry. For a given aeroshell shape, FTPS composition, and baseline entry trajectory, critical FTPS and IS maximum temperatures and their corresponding uncertainties must be predicted to prescribe the FTPS thickness and determine a corresponding nominal entry heat load constraint. Figure 3 shows the external heating drivers on the RV during atmospheric entry. Note that the bulk of the aftbody is not covered by FTPS and the aft-side toroid skin is directly exposed to wake convective heating during entry. The wake heating loads are relatively low, and therefore it was decided that aft-side FTPS would not be necessary.

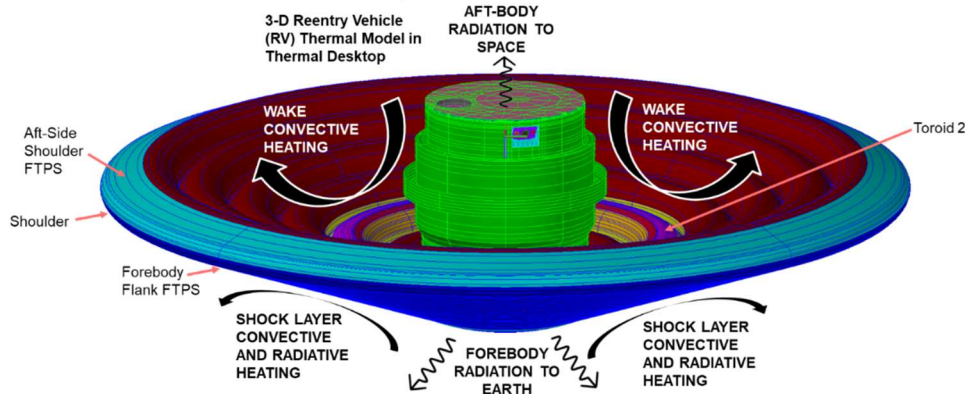


Fig. 3 RV Thermal Model Geometry and Thermal Boundary Conditions

A diagram of the one-dimensional FTPS thermal model showing components and boundary conditions is shown in Figure 4. The most critical temperature prediction is the maximum FTPS/IS interface (IF) temperature, where the FTPS gas barrier touches the IS on the deployable aeroshell forebody flank. The location of the FTPS/IS interface is shown in Figure 2 and Figure 4 as interface 7. Another critical aeroshell temperature prediction is the maximum aft-side IS toroid skin temperature, where the toroid is exposed directly to wake heat loads.

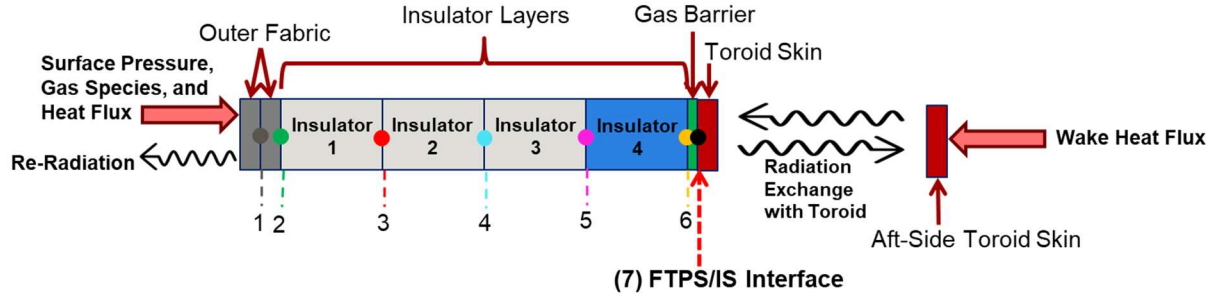


Fig. 4 One Dimensional FTPS Thermal Model Diagram

Figure 5 depicts locations on the aeroshell where temperatures are predicted for atmospheric entry. Points 1 and 2 shown in Figure 5 are the two critical thermal analysis locations mentioned. The FTPS layout shown in Figure 2 is constant across the forebody flank (outboard of the nose/flank junction).

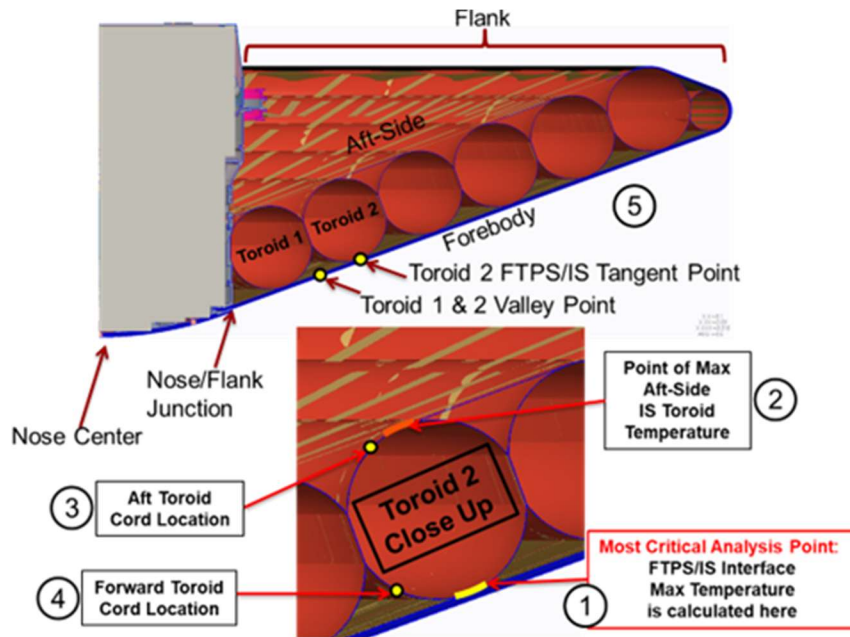


Fig. 5 Aeroshell Critical Thermal Design Locations

B. Probabilistic Thermal Margin Process

There is uncertainty in the critical temperature predictions due to the uncertainties that exist in atmospheric entry aeroheating environments, the thermal response of the FTPS/IS materials, as well as the accuracy of computational models themselves. These uncertainties are mitigated by sizing the FTPS thickness, tailoring the planned entry heat load, and applying temperature limit safety factors in order to apply thermal margin to the FTPS design. The initial entry state (entry velocity, flight path angle, and entry mass) significantly drives the expected atmospheric entry conditions and resulting heat load that the RV will experience. After the FTPS was designed such that aeroshell thermal response is predicted to be in the ballpark acceptable limits, LOFTID's initial entry state was tailored to fine tune the predicted thermal response so it would survive entry with the desired level of reliability by using the probabilistic margin process. The probabilistic margin process used to calculate the reliability of the aeroshell was

carried out by an uncertainty analysis method which employs an end-to-end Monte Carlo simulation (discussed in Section III). The end-to-end Monte Carlo simulation propagates the uncertainties in the trajectory and aeroheating model into the FTPS and RV thermal models to quantify the resulting probability distribution of the FTPS/IS thermal response, more specifically, the maximum critical temperatures at locations 1 and 2 in Figure 5.

As mentioned previously, LOFTID is an experimental flight, and as such the project's "2-sigma" reliability standard dictates that the aeroshell be margined such that there is at least a 97.7% chance of flying within allowable parameters (maximum temperatures). This means that the critical aeroshell locations should have less than a 2.3% chance of exceeding their allowable temperatures. The calculated maximum critical temperature probability distributions are used to determine the expected maximum critical temperatures (T_{Exp}) and the probabilities of exceeding their flight allowable temperatures (T_{Allow}) and temperature limits (T_{Limit}) for a particular FTPS size and nominal entry heating profile. Additionally, the maximum critical temperatures at which there is a 97.7% chance of not exceeding is calculated ($T_{97.7_Calc}$). For example, if the maximum FTPS/IS interface probability distribution shows that there is a 97.7% chance of not exceeding 405°C, then $T_{97.7_Calc}$ (or 97.7 percentile) is defined as 405°C.

The flight allowable temperature is defined as a critical component's upper temperature limit (T_{Limit}) minus a safety temperature delta (T_{Safe}). The temperature limit was determined by ground tests on toroid skin samples in flight-relevant thermal environments. The safety delta is a knockdown on T_{Limit} that accounts for any potential discrepancies between flight and toroid skin failure limit ground tests and unknown-unknowns in general.

The thermal performance margin is defined as the difference between the expected maximum critical temperature and its allowable temperature ($T_{Allow} - T_{Exp}$). In order to margin the aeroshell according to LOFTID's reliability standard, the FTPS and entry heating profile should be tailored so that the critical aeroshell temperatures are calculated to have less than or equal to a 2.3% chance of exceeding their allowable temperatures. In other words, the performance margin ($T_{Allow} - T_{Exp}$) should be greater than or equal to the temperature difference between T_{Exp} and $T_{97.7_Calc}$ ($T_{97.7_Calc} - T_{Exp}$). The thermal performance margin deficit indicates approximately how much more performance margin is needed to satisfy the reliability standard and is calculated as $T_{97.7_Calc} - T_{Allow}$. A negative margin deficit would mean the system is over-margined whereas a positive margin deficit indicates the system is under-margined according to the project's reliability standard.

Figure 6 displays an example visualization of the performance margin, performance margin deficit, and the thermal performance parameters (T_{Allow} , T_{Limit} , and T_{Safe}) relative to the calculated nominal (T_{Nom}) and expected (mean) maximum critical temperatures (T_{Exp}). The offset between the nominal and expected maximum critical temperature prediction is primarily due to the model error bias (discussed in Section III.D) and asymmetric probability distributions of uncertain trajectory, aerothermal, or thermal response parameters. The bell curve in Figure 6 represents an idealized histogram of maximum FTPS/IS interface temperature dispersions resulting from an end-to-end Monte Carlo simulation.

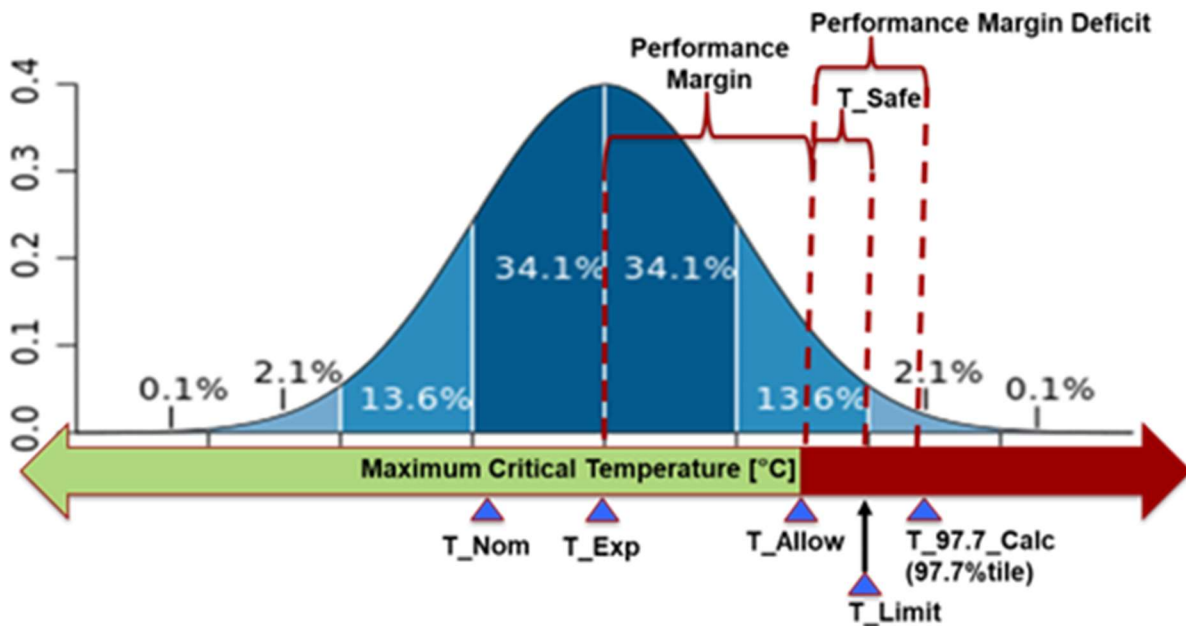


Fig. 6 Example of Probabilistic Thermal Margin Parameters

A performance margin deficit can be eliminated or turned negative by taking measures to lower the expected interface temperature, which results in moving T_97.7_Calc to the left in Figure 6. This can be accomplished by adding thermal protection to the aeroshell (FTPS thickness), modifying the nominal entry state to decrease the nominal entry heat load, or reducing conservatism in the thermal response models. The FTPS thickness can only be coarsely adjusted in increments of the thickness of a layer of insulation, which causes relatively large changes in the expected interface temperature. Conversely, altering the nominal entry heat load can more finely tune the expected interface temperature. The amount of fine tuning available comes from the performance capabilities of the upper stage orbit transfer vehicle and must be balanced with primary payload launch window margins, other flight timeline constraints, and payload mass. If mission constraints do not allow fine tuning mitigations to remedy the thermal performance margin, then FTPS may be added as a course adjustment at the potential expense of a perhaps overly-conservative margined system.

III. End-to-End Monte Carlo Uncertainty Propagation Approach

In the previous section, the critical aeroshell performance locations were defined and the margin process was described with defined aeroshell thermal performance metrics (T_Nom, T_Exp, T_Allow, T_Limit, T_97.7_Calc, etc.). This section discusses the uncertainty propagation approach to quantify the probability distributions of maximum FTPS/IS interface temperature and maximum aft-side toroid skin temperature which are used to calculate the thermal performance metrics. As noted in the previous section, an end-to-end Monte Carlo process is used to propagate the uncertainty in the trajectory, aerothermal, and thermal models to quantify the uncertainty in the maximum aeroshell temperatures, as shown by the diagram in Figure 7. In Figure 7, The FTPS Thermal Model is shown to be coupled to the RV Thermal model because the predicted aft-side toroid skin thermal response (location 2 in Figure 5) does affect the predicted maximum FTPS/IS interface temperature (location 1 in Figure 5) and this coupling is taken into account in the thermal models that the Monte Carlo simulation operates on, as described in Section III.D (Figure 9).

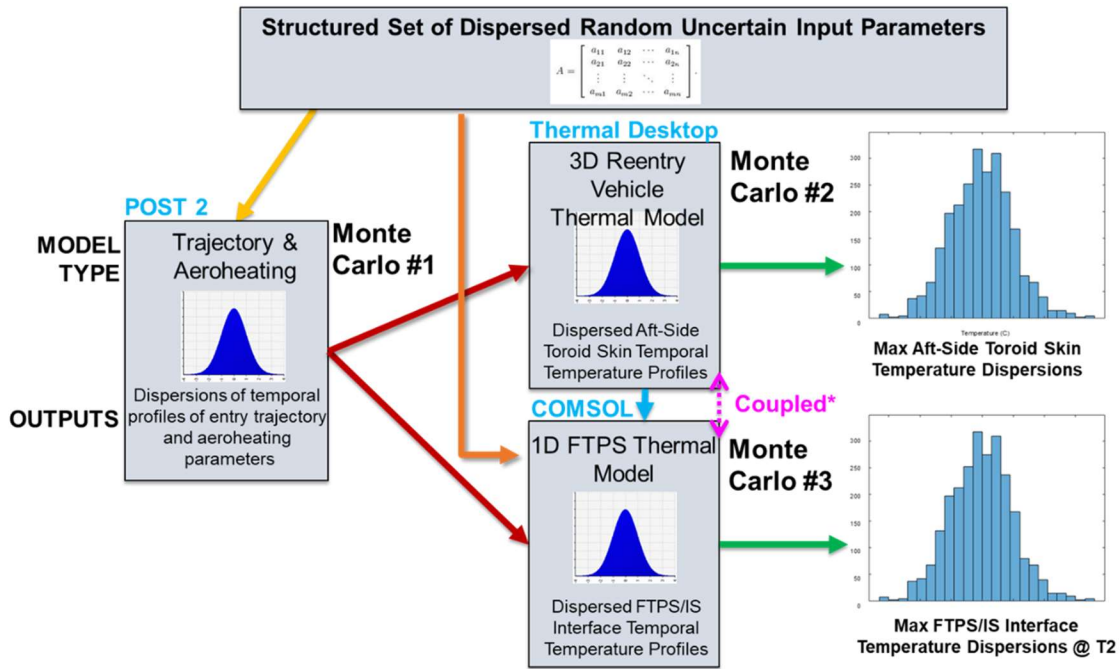


Fig. 7 Uncertainty Analysis Process using the End-to-End Monte Carlo Simulation Approach

The process begins with generating a structured set of uncertain input parameters samples that include parameters from each of the model disciplines, including trajectory, aerothermodynamics, and material thermal response. The uncertain parameters are then propagated through the computational models of the respective disciplines. Each model is run 2000 times starting with the trajectory and aerothermal models and then proceeding to the material thermal response models, each case with a random sampling of the uncertain input parameters. Each discipline model provides output, or linking variables, which are required for input to another discipline model. For example, the desired uncertain output from the trajectory model, given trajectory-specific uncertain parameter inputs, are the temporal

profiles of atmospheric quantities (i.e., density and velocity). These temporal profiles are provided as an input to the aerothermodynamics model. The resulting aeroheating and surface pressure profiles are then provided as inputs for the material thermal response models, which finally results in the 2000 dispersions of FTPS/IS interface and aft-side toroid skin temperature temporal profiles. The maximum of these critical temperatures is then extracted from the respective set of temporal profiles to construct a histogram of the maximum interface temperature and maximum toroid skin temperature as performance quantities of interest. The details associated with each of the components in Figure 7 are described further in the following subsections.

A. Sample Generation

A set of 2000 samples are generated for a total of 74 uncertain variables, which are inputs to either the trajectory, aerothermal, or thermal models, using Latin Hypercube structured sampling [5]. Latin Hypercube sampling has been used since the 1970's for Monte Carlo studies as a technique for reducing the required number of samples to converge the statistics of a desired output. The approach is to sample from the domain using partitions based on the probabilistic distribution of each uncertain input variable, rather than the common practice to randomly sample based on the probabilistic distribution alone for each of the uncertain input variables. Partitioning of the uncertain sample space allows for sampling near the domain boundaries, which corresponds to the upper and lower bounds of the uniformly distributed variables and the tails of normally distributed variables.

Each of the 2000 samples corresponds to 2000 trajectories with each having a unique set of trajectory, aerothermal, and thermal uncertain input variables. Uncertainties in vehicle and entry conditions used in the trajectory models define the trajectories. Each trajectory is assigned scale factors for constructed aerothermal indicators. Each trajectory is also assigned a set of thermal uncertain variables. The characterization of these uncertain parameters is explained for each discipline, including assumptions for the models used, in the next few subsections.

B. Trajectory Models and Uncertainties

The Program to Optimize Simulation Trajectories II (POST2) is used to compute the trajectories for the end-to-end Monte Carlo study [6]. For this study, POST2 simulates six degree-of-freedom vehicle motion and environments, beginning at initial orbital conditions at separation from the launch vehicle and ending at Mach 0.75, with output at 0.25-second intervals. Aerothermal convective and radiative indicators are used within POST2 to compute the unmargined aeroheating parameters as a function of atmospheric density, atmospheric relative freestream velocity, and RV total angle of attack. These aeroheating parameters are needed for the thermal model at several body point locations including the nose, nose-cone juncture, shoulder, and afterbody. A fixed HIAD diameter of 6 meters is assumed with a nominal initial roll rate of two revolutions per minute and zero nominal initial tip-off rate. The initial vehicle attitude is nominally targeted such that 0-deg total angle of attack is achieved at entry interface of 125 km altitude.

The 2000 trajectories computed in the end-to-end Monte Carlo include 58 uncertainties consisting of mass properties, aerodynamics, and initial entry states, attitude, and roll/tip-off rates. The entry mass is assumed to be known within 1.1% at day of launch, and center-of-gravity location and moments/products of inertia are varied to account for the uncertainty in RV configuration during mass properties testing. All of the 34 aerodynamic uncertainties are assigned variations utilizing heritage statistical data from Mars Science Laboratory and other previous missions [7-11]. The initial entry states, attitude, and tip-off rates are varied according to expected uncertainty on the day of launch. The atmosphere is modeled using Earth Global Reference Atmospheric Model (Earth-GRAM 2010) version 4.0 [12], and these variations are handled internally using Markov and wave processes. The sampling process described in Section III.A does not currently control these uncertainties in the atmosphere.

C. Aerothermodynamic Models and Uncertainties

As noted in the previous subsection, aerothermal forebody convective and radiative indicators are included in POST2 to compute the aerothermal parameters needed for the FTPS thermal model at the nose-cone junction body point near Toroid 2. The aerothermal indicators were developed using previous design-cycle trajectories with high-fidelity computational fluid dynamics (CFD) at several points and verified for the trajectory considered in the current design cycle. Two aerothermal parameters, the enthalpy-based convective heat transfer coefficient (C_H) and the radiative heat flux (q_{rad}) to the vehicle surface, can be tracked from the CFD runs and correlated with curve fits as a function of freestream density (ρ_∞), velocity (V_∞), and angle of attack (α), as shown in Eqs. (1) and (2).

$$C_H = k_{CH} * \alpha * \rho_\infty^m(\alpha) * V_\infty^n \quad (1)$$

$$q_{rad} = k_{rad} * \alpha * \rho_\infty^m * V_\infty^n \quad (2)$$

In Eqs. (1) and (2), α , m , and n are the curve-fit parameters. A multiplier approach is used to account for the thermochemistry, catalysis, and radiation uncertainties, where the multiplier factors k_{CH} and k_{rad} in Eqs. (1) and (2), are varied according to the uncertainty information derived from axisymmetric forebody computations for 15 points along 2000 trajectories, given freestream velocity, density, and angle of attack, from POST2. The Langley Aerothermodynamic Upwind Relaxation Algorithm (LAURA) CFD solver is used to compute the flow field around the forebody surface for a 5-species gas composed of N₂, O₂, NO, N, and O. The High Temperature Air Radiation Algorithm (HARA) is coupled with LAURA to compute the radiative transport to the surface. Five chemical reaction rates [13], 15 collision integrals for the possible species collision pairs [14], catalytic recombination efficiency positive bias of up to 10% above the catalysis model reported by Stewart for outer fabric cloth material [15], and 11 heavy-particle excitation rates for N₂ and NO molecular bands [16] were varied to quantify the uncertainty in the convective heat transfer coefficient and radiative heat flux at the nose-cone juncture body point along the vehicle surface. Given the heat transfer coefficient and radiative heat flux data at this body point, the multiplier coefficient can be computed by comparing (dividing) the CFD-computed values by the aerothermal indicator predictions for each of the 15 trajectory points. The most conservative uncertainty was determined to be at the peak heating trajectory point. A probability distribution fitting algorithm is then used to estimate the statistics for the multiplier data at the peak heating trajectory point. In addition to the two multiplier uncertainties above for the convective and radiative heating indicators on the forebody, a multiplier uncertainty range of -25% to +25% is applied to the convective heating indicator for the aft body points that correspond to the toroid skin exposed to the wake flow. The uncertainty range is conservatively estimated by the cognizant CFD analyst expert.

D. Thermal Models and Uncertainties

A one-dimensional (1-D) physics-based thermal model using COMSOL software (depicted in Figure 4) is used to solve the thermal response of the FTPS in the presence of external pressure and aerodynamic heating loads. Heat transfer is modeled within the FTPS layers using several modes including solid conduction, radiation, gas conduction, and material decomposition. The temporal temperature profile and spatial temperature distribution throughout the layered FTPS thickness is solved by the conservation equations governing heat and decomposition gas mass transfer through a porous solid dependent on local temperature, pressure, and gas species concentrations. The FTPS layout considered for this study consists of two outer fabric layers, four insulation layers, and one gas barrier layer in contact with the Toroid 2 skin as shown in Figure 2 and Figure 5 (Point 1).

A three-dimensional (3-D) RV thermal model developed in Thermal Desktop (depicted in Figure 8 and Figure 3) solves the thermal response of the toroid IS to the entry heating environment. The heat transfer physics involved in this model include aeroshell aft-side wake convective heat loads, conduction through the toroid inflatable structure material and interfaces, radiation heat transfer within the toroids and between the FTPS and IS, and re-radiation to Earth and Space.

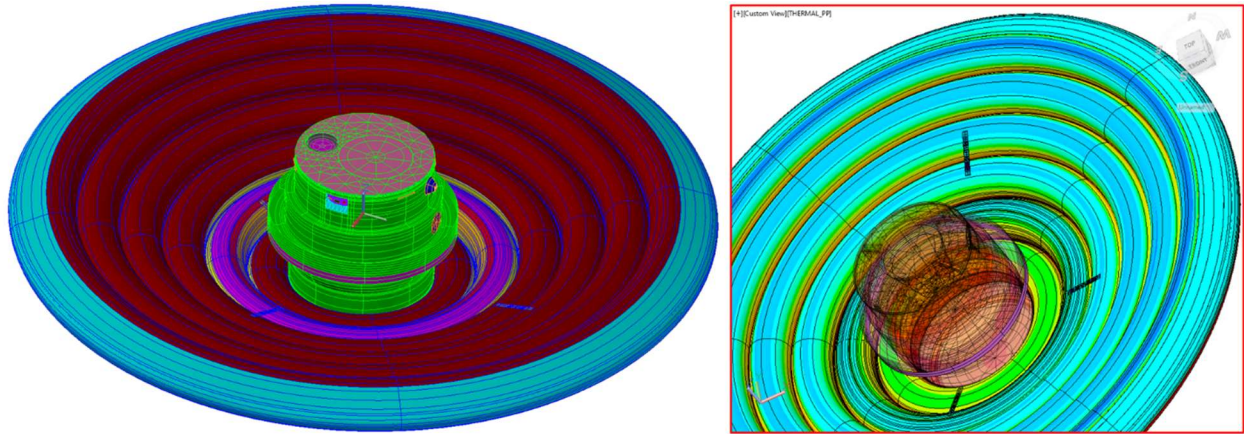


Fig. 8 Aeroshell Thermal Model (Thermal Desktop)

The 1-D FTPS and 3-D RV thermal models are coupled by infrared radiation interaction between the FTPS and IS. Figure 9 illustrates this coupling. The aft-side toroid skin and the FTPS/IS interface are assumed to be exchanging radiation in opaque and gray two surface enclosures assuming a physically accurate view factors between the surfaces. The 1-D FTPS thermal model and 3-D RV thermal model are run sequentially in an iterative fashion to converge on

the FTPS/IS interface temperature temporal profile solution. To enable this process, an effective toroid interior radiation sink temperature is calculated from the RV thermal model solution by averaging the solved temperatures at the points in green and yellow regions shown in Figure 9. These radiation sink temperature profiles are passed to the 1-D FTPS thermal model as the prescribed aft-side toroid skin temperature boundary condition applied to the component labeled as “Aft-Side Toroid Skin” in Figure 4. The 1-D FTPS thermal model then solves the FTPS/IS interface temperature at the gas barrier and that solution is applied at a temperature boundary condition in the 3-D aeroshell thermal model as indicated by the magenta or red arrows and surfaces in Figure 9. The 1-D FTPS model temperature solution at the FTPS/IS interface (aft side of the gas barrier) is assumed to apply uniformly over the entire local area that it is in contact with the toroid (“Tangent Point,” red area in Figure 9) or tented over a toroid valley (“Valley Point,” magenta area in Figure 9) because flank spatial surface heat flux gradients are very low. The iterative exchange of temperature boundary conditions between the 1-D FTPS and 3-D aeroshell thermal models continues until the FTPS/IS interface temperature converges.

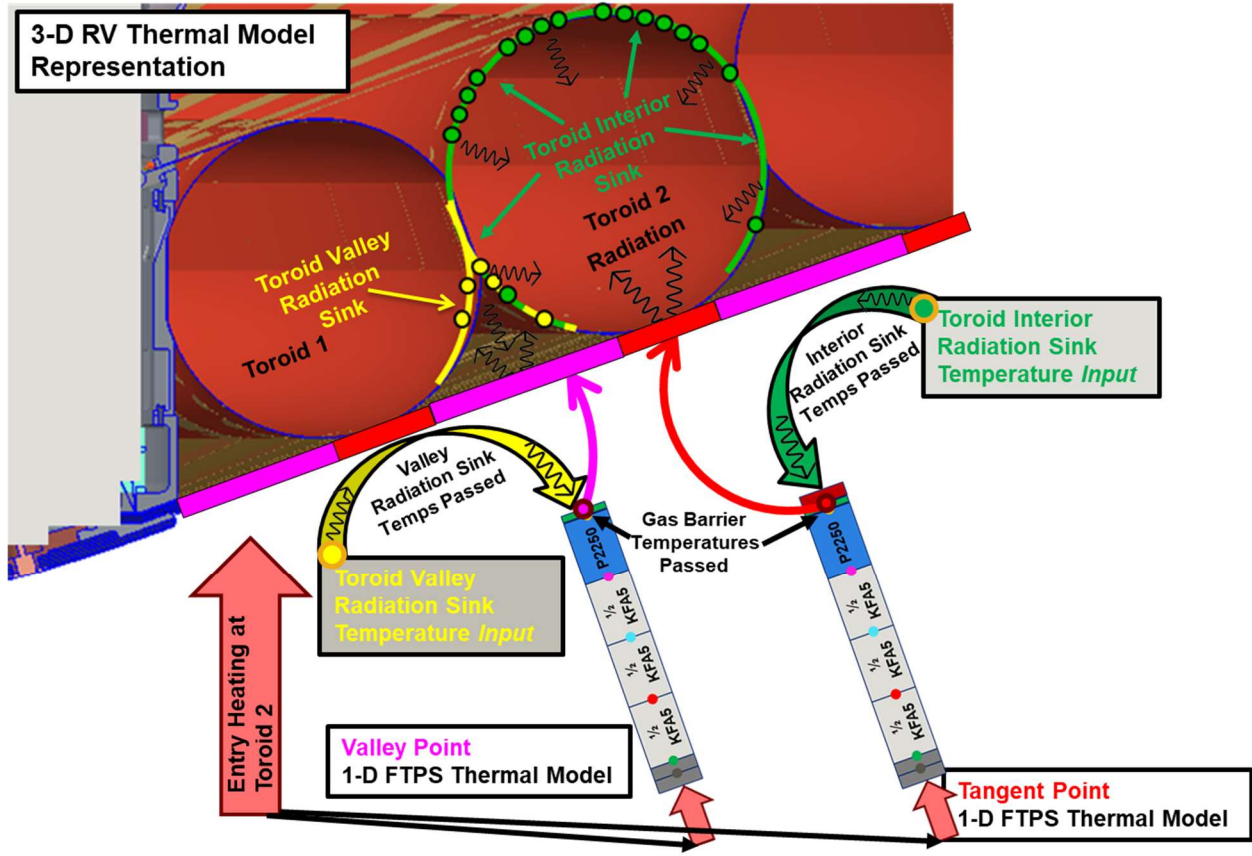


Fig. 9 Coupling between the 1-D FTPS and the 3-D RV Thermal Models

The net heat rate on the FTPS surface is applied to the 1-D thermal model according to Eq. (3):

$$q_{\text{net}} = C_H(H_{0e} - H_w) + q_{\text{rad}} - \epsilon \sigma T_w^4 \quad (3)$$

Here, the 2000 aerothermal parameter temporal profiles, calculated using Eqs. (1) and (2), are used to drive the thermal response models which compute the transient temperature dispersions. The total enthalpy, H_{0e} , is calculated within the POST2 code based on freestream velocity and temperature. The wall enthalpy, H_w , is computed using species-dependent enthalpy curve fits from LAURA’s thermodynamic database and an assumed wall species composition of 79% N₂, 21% O₂, by mass. In addition to the 2000 aerothermal parameter temporal profiles, 13 thermal uncertain parameters are varied, including thermal properties (specific heat and thermal conductivity) of the outer fabric and insulation, activation energy for decomposition of the insulation, biases for the outer fabric emissivity, and a maximum interface temperature error bias [1,15]. The uncertainties are assigned based on expert opinion and/or previous testing. The maximum interface temperature model error bias is derived from arc-jet testing to quantify inaccuracies in the

model compared to test data due to model-form inaccuracies, FTPS aging effects (due to compression cycles), insulator property non-uniformity/variability, and multidimensional effects.

IV. Results and Discussion

Using the end-to-end Monte Carlo uncertainty analysis process, the probability distributions of critical aeroshell thermal response metrics were calculated. From this information, the risk of aeroshell over-temperature was calculated at critical analysis locations 1 and 2 shown in Figure 5. This section covers the statistical parameters gathered for the FTPS/IS interface and IS toroid skin thermal responses to atmospheric entry heating.

Note that the statistics and margins reported in this paper are not LOFTID analysis results but are representative of the statistics in the ballpark of what may be seen in earlier stages of the design iteration process, and are presented as an example for the purpose of an academic demonstration of the probabilistic thermal response uncertainty analysis method and its uses.

A. Aft-Side Toroid Skin Thermal Response Statistics

Figures 10 and Figure 11 show example results from a Monte Carlo #2 (represented in the Figure 7 block diagram) in the end-to-end process. Plotted in Figure 10 is the set of dispersed toroid skin temporal temperature profiles. From that data, the 97.7% percentile maximum toroid temperature is extracted and is shown not to exceed the flight allowable temperature. Therefore, the calculated risk of exceeding T_{Allow} is effectively calculated as 0%, and it could be stated that aeroshell is calculated to be 100% reliable not to exceed the flight allowable aft-side toroid skin temperature. Plotted in Figure 11 is the set of dispersed effective toroid interior radiation sink temporal temperature profiles. Each sample from this set of profiles is passed into the corresponding Monte Carlo #3 sample FTPS thermal model as the aft-side toroid skin temperature radiation sink temperature boundary condition.

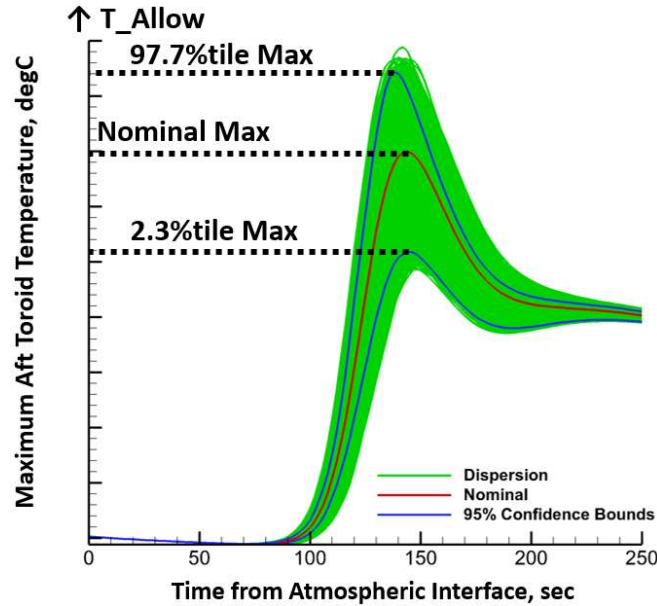


Fig. 10 Monte Carlo #2 Example Results - Maximum Aft-Side Toroid Skin Temperature Profile Dispersions

Although the aft-side IS toroids are directly exposed to wake convective heating, the uncertainty analysis shows that there is high confidence that the toroid skin will not exceed flight allowable temperature. In fact, it is over-margined as indicated by the negative performance margin deficit. No mitigations would be recommended to thermally protect the aft-side IS skin or ease environments. The same analysis was also completed for aft-side exposed structure straps for LOFTID, but example results are not shown in this paper.

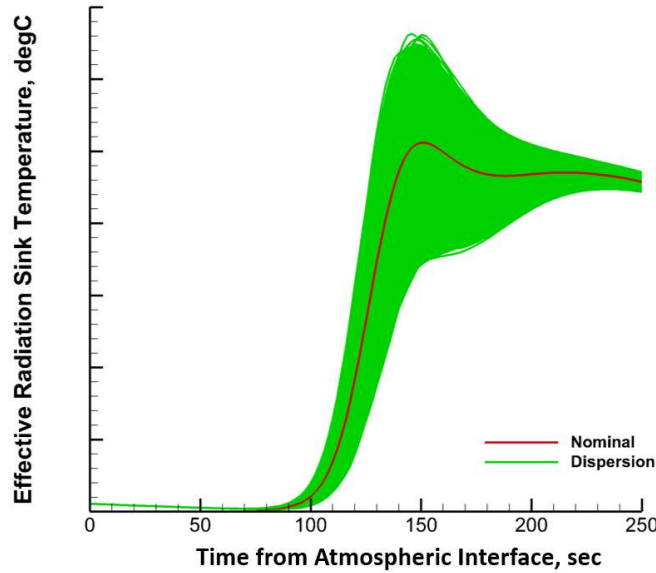


Fig. 11 Monte Carlo #2 Example Results - Toroid Interior Radiation Sink Temperature Profile Dispersions

B. FTPS/IS Interface Thermal Response Statistics

Figure 12 and Figure 13 show example results from Monte Carlo #3 (represented in the Figure 7 block diagram) in the end-to-end process. Figure 12 shows that after 2000 samples of the FTPS thermal model are run, the standard deviation of the maximum FTPS/IS interface temperature has sufficiently converged which indicates a sufficient number of Monte Carlo samples to give accurate statistics.

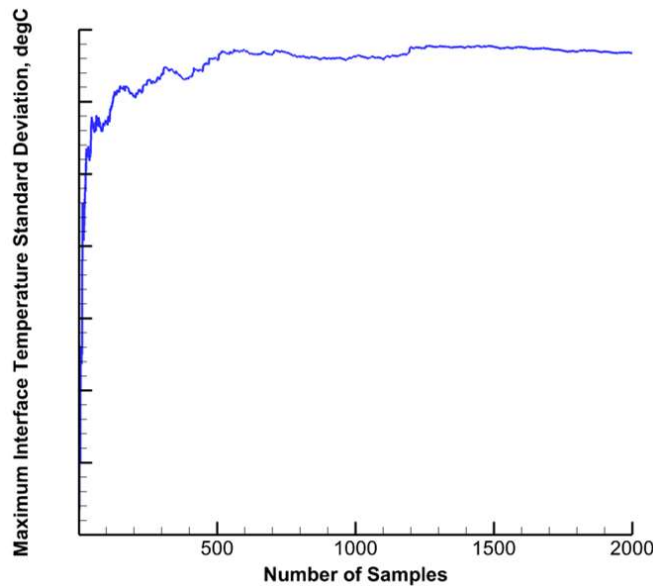


Fig. 12 Monte Carlo #3 Example Results - Convergence of Maximum FTPS/IS Interface Temperature Standard Deviation

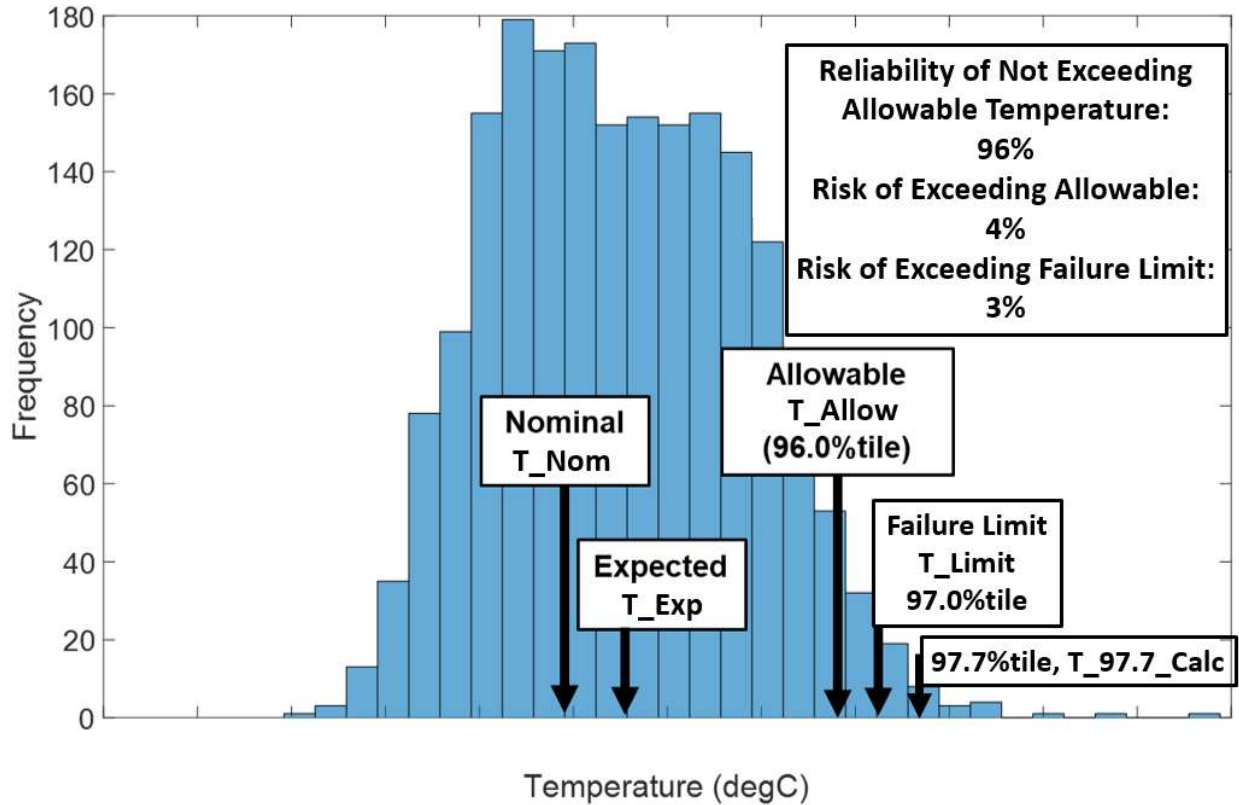


Fig. 13 Monte Carlo #3 Example Results – 2000 Sample Histogram of Maximum FTPS/IS Interface Temperature

Plotted in Figure 13 is an example histogram of the dispersed maximum FTPS/IS interface temperature. From the statistics supplied by the histogram data, the 97.7 percentile ($T_{97.7_Calc}$) and the expected max temperature (T_{Exp}) can be extracted, and the performance margin is calculated to be $T_{97.7_Calc}$ minus T_{Exp} . Additionally, the performance margin deficit is calculated to be $T_{97.7_Calc}$ minus T_{Allow} . On the example histogram plot, it is shown that the 97.7 percentile max FTPS/IS interface temperature is above the flight allowable temperature at the 96.0 percentile. Therefore, the aeroshell thermal performance would be considered to be under-margined according to a “2-sigma” 97.7% reliability standard as the aeroshell is calculated to be only 96.0% reliable to maintain max temperatures below the allowable. Furthermore, the probability of reaching the temperature at which inflatable structure material is expected to fail (based on thermal testing) is 3% in this example, which would likely not be acceptable. Even if the calculated risk of exceeding the allowable is acceptable, the statistics may show that there still a significant non-zero risk of failure due to over-temperature that may cause some concern and desire to mitigate.

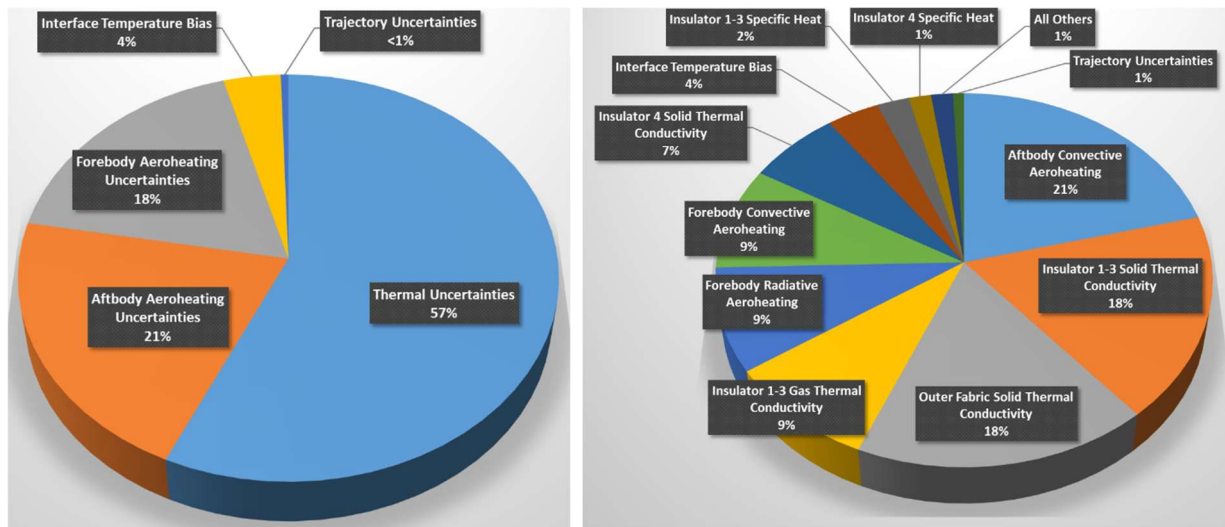
The calculated FTPS reliability, performance margin deficit, and unacceptable probability of IS material failure would indicate that measures should be taken to lower the expected FTPS/IS interface temperature by bolstering the FTPS or managing the entry heat load. Since the thermal reliability of the aeroshell (96.0%) is very close to the project’s standard (97.7%) no additional FTPS would be required, and mitigations would be made by fine tuning the entry heating environment only. First, it would be recommended that adjustments be made to the initial entry state of the trajectory to lower the resultant entry heat load. This can be done by either lowering the initial entry velocity, steepening the entry flight path angle, lowering the entry mass, or some combination of the three. The calculated reliability of the FTPS could also be increased by reducing some of the conservatism in the thermal response models by increasing model fidelity or performing additional thermal testing. The specific FTPS material properties to perform additional testing can be informed by the maximum FTPS/IS interface temperature uncertainty sensitivity breakdown discussed in the next sub-section. Project funds should be more focused on improving understanding (decreasing uncertainty) in the uncertain parameters that have larger influence on the cumulative aeroshell thermal response uncertainty.

The final thermal response uncertainty analysis results verifying the LOFTID FTPS and entry-flight designs showed that the 97.7 percentile maximum FTPS/IS interface temperature was comfortably below the maximum flight

allowable temperature. After post-flight data analysis, it was observed that the actual maximum FTPS/IS interface temperature was well below the 97.7 percentile and also below the calculated expected value but above the calculated 2.3 percentile. This indicates that the aeroshell thermal design was sufficiently margined without being overly conservative. A goal achieved by this probabilistic uncertainty analysis process was ensuring max interface temperature would be above a desired level to drive the FTPS and IS to adequately high temperatures for useful thermal response reconstruction and model correlation.

C. Maximum FTPS/IS Interface Temperature Uncertainty Sensitivity Breakdown

As noted in the previous subsection, there are three possible options to manage the reliability of the FTPS through evaluation of the FTPS/IS interface temperature to meet project standard, one of which is performing additional verification tests to refine parameters that significantly contribute to the overall total variance in the output quantity of interest (i.e., FTPS/IS interface temperature). In order to assess these individual uncertain variable contributions, a sensitivity analysis was performed using a Sobol indices approach [18]. Figure 14a presents the fractional contributions of each discipline (thermal, aeroheating, interface temperature bias, and trajectory) to the overall uncertainty in the FTPS/IS interface temperature. The results show that the FTPS material thermal and aeroheating (forebody and aftbody) are the uncertainties which significantly outweigh other areas accounted in the Monte Carlo propagation. Figure 14b provides a more detailed breakdown of the fractional contributions for individual uncertain variables. In Figure 14b, the top six contributors with greater than approximately 10% influence to the overall FTPS/IS interface temperature variance include all aeroheating modes, the thermal conductivity of insulator layers 1-4, and the outer fabric thermal conductivity. These results provide specific insight for the engineers to focus attention in reducing, or refining, the uncertainty in specific inputs to the end-to-end Monte Carlo process through additional verification tests.



a) By discipline Area

b) By each individual uncertain variable

Fig. 14 Maximum FTPS Interface Temperature Uncertainty Sensitivity Breakdown

D. Comparison to Traditional RSS TPS Margin Approach

LOFTID FTPS size was compared to the size resulting from NASA's traditional root sum squared (RSS) TPS thickness margin process [19]. The RSS process was run to hypothetically size the FTPS insulation using predicted LOFTID entry environments and the FTPS thermal model. The sizing was done to target a maximum FTPS/IS interface temperature equal to the final LOFTID calculated 97.7 percentile maximum temperature ($T_{97.7_calc}$) for an apples-to-apple comparison. This target temperature which drives FTPS sizing will be referred to as the "maximum interface target temperature." Targeting this interface temperature in the RSS process essentially sizes the FTPS assuming the same "2-Sigma" risk posture that LOFTID had taken.

The RSS process involves sizing the FTPS insulation thickness for three separate analysis cases utilizing the the FTPS thermal model, with varying entry aeroheating loads applied. Case 1 applies the +2-Sigma heat load trajectory (~97.7 percentile from trajectory dispersions), with the nominal aerothermal response and FTPS material properties

assumed. The FTPS is sized to yield the maximum interface target temperature and the resulting thickness is denoted as T_1 . Case 2 also assumes nominal FTPS material properties but applies the +2-Sigma aerothermal uncertainty factors to the Case 1 aeroheating environment, and the resulting FTPS thickness required to yield the maximum interface target temperature is denoted as T_2 . Finally, Case 3 uses the Case 1 aeroheating environments, but accounts for uncertainty in the FTPS material properties by sizing the FTPS insulation thickness to yield a lower interface target temperature and the resulting FTPS thickness is denoted as T_3 . Equations (4) and (5) are solved to arrive at the final required FTPS insulation thickness, where T_b is the baseline FTPS thickness and T_F includes a 1.10 factor of safety.

$$T_b = T_1 + \sqrt{(T_2 - T_1)^2 + (T_3 - T_1)^2} \quad (4)$$

$$T_F = 1.10 \times T_b \quad (5)$$

Sizing the FTPS insulation using the RSS process would yield an insulation size (T_F) that is at least 26% thicker than the LOFTID FTPS insulation which was sized by the probabilistic thermal margin approach. The extra FTPS thickness prescribed by the RSS method would have added volume and mass to the heat shield and prevented the inflatable structure from reaching the minimum desired maximum temperature for the LOFTID flight demonstration.

V. Conclusion

This paper presents an overview of the probabilistic thermal margin process for an inflatable aeroshell. The presented thermal margin process is a departure from the traditional approach of supplying conservatively bounding-case trajectory and aeroheating environments to drive TPS sizing. The end-to-end Monte Carlo simulation links the trajectory and aerothermal model dispersions to the aeroshell thermal response models to propagate uncertainty from the entry environment to the maximum critical aeroshell temperature predictions. This probabilistic margin process informs mitigations needed to achieve acceptable thermal performance reliability without applying unnecessary margin which would be counterproductive for a flight demonstration mission. The uncertainty analysis provided the necessary predicted aeroshell thermal performance metrics to inform various mitigation options to refine design margin, which include adjustments to the entry trajectory/mass, reduction in conservatism in the thermal models, additional testing, or a combination thereof.

The end-to-end Monte Carlo thermal response uncertainty analysis and margin process was applied to the LOFTID FTPS and flight design, which produced several useful benefits for the inflatable heat shield technology demonstration. The process allowed for more informative risk and design trades to drive strategic atmospheric entry trajectory parameter selection. The FTPS was sized with adequate margin which kept the inflatable structure comfortably below temperature limits without being overly conservative. This allowed the FTPS to be sufficiently stressed to prove its capability as an EDL technology, and flight data showed that the hottest point on the inflatable structure reached a maximum temperature that exceeded the minimum project goal. Additionally, no failures occurred in flight due to thermal overload. This favorable aeroshell thermal response to the flown entry environment supplied useful flight data to demonstrate the technology application and to validate thermal models, so they can be developed as better HIAD design tools future EDL applications. Although this paper focuses on the application of the probabilistic margin process for a HIAD thermal protection system, this methodology can also be applicable to other entry system types and related engineering disciplines within the EDL field.

References

- [1] Tobin, S. A. and Dec, J. A., "A Probabilistic Sizing Demonstration of a Flexible Thermal Protection System for a Hypersonic Inflatable Aerodynamic Decelerator", AIAA 2015-1895, 53rd AIAA Aerospace Sciences Meeting, Jan. 2015
- [2] Dec, J. A. and Mitcheltree, R. A., "Probabilistic Design of A Mars Sample Return Entry Vehicle Thermal Protection System," AIAA Paper 2002-0910.
- [3] Cozmata, I., Wright, M. J., Laub, B., Willcockson, W., H., "Defining Ablative Thermal Protection System Margins for Planetary Entry Vehicles," 42nd AIAA Thermophysics Conference, AIAA 2011-3757, Honolulu, Hawaii, June 2011.
- [4] Wright, M. J., Bose, D., and Chen, Y.-K., "Probabilistic Modeling of Aerothermal and Thermal Protection Material Response Uncertainties," AIAA Journal, Vol. 45, No. 2, 2007, pp. 399-410. doi: 10.2514/1.26018.
- [5] Iman, R. L., and Shortencarier, M. J., "A Fortran 77 Program and User's Guide for the Generation of Latin Hypercube and Random Samples for Use with Computer Models," NUREG/CR-3624, Technical Report SAND83-2365, Sandia National Laboratories, Albuquerque, NM, 1984.
- [6] Bauer, G.L., Cornick, D.E., and Stevenson, R., "Capabilities and Applications of the Program to Optimize Simulated Trajectories (POST)." NASA CR-2770, February 1977.

- [7] Gnoffo, P. A., Braun, R. D., Weilmuenster, K. J., Mitcheltree, R. A., Englund, W. C., Powell, R. W., "Prediction and Validation of Mars Pathfinder Hypersonic Aerodynamic Database", *Journal of Spacecraft and Rockets*, Vol. 36, No. 3, May-Jun 1999, pp. 367-373.
- [8] Olds, A. D., Beck, R. E., Bose, D. M., White, J. P., Edquist, K. T., Hollis, B. R., Lindell, M. C., Cheatwood, F. M., "IRVE-3 Post-Flight Reconstruction", AIAA 2013-1390, March 2013.
- [9] Schoenenberger, M., Van Norman, J. W., Karlgaard, C., Kutty, P., Way, D., "Assessment of the Reconstructed Aerodynamics of the Mars Science Laboratory Entry Vehicle", *Journal of Spacecraft and Rockets*, Vol. 51, No. 4, Jul-Aug 2014, pp. 1076-1093.
- [10] Moss, J. N., Glass, C. E., Hollis, B. R., Van Norman, J. W., "Low-Density Aerodynamics for the Inflatable Reentry Vehicle Experiment", *Journal of Spacecraft and Rockets*, Vol. 43, No. 6, Nov-Dec 2006, pp. 1191-1201.
- [11] Edquist, K. T., Desai, P. N., Schoenenberger, M., "Aerodynamics for Mars Phoenix Entry Capsule", *Journal of Spacecraft and Rockets*, Vol. 48, No. 5, Sept-Oct 2011, pp. 713-726.
- [12] F. Leslie and C. Justus, "The NASA Marshall Space Flight Center Earth Global Reference Atmosphere Model - 2010 Version." NASA/TM-2011-216467, 2011, Marshall Space Flight Center, Huntsville, AL.
- [13] West, T. and Johnston, C. O., "Uncertainty and Sensitivity Analysis of Afterbody Radiative Heating Predictions for Earth Entry", *Journal of Thermophysics and Heat Transfer*, Vol. 31, No. 2 (2017), pp. 294-306.
- [14] Wright, M., Bose, D., Palmer, G., and Levin, E., "Recommended Collision Integrals for Transport Property Computations Part 1: Air Species", *AIAA Journal*, Vol. 43, No. 12 (2005), pp. 2558-2564.
- [15] Stewart, D., "Determination of Surface Catalytic Efficiency for Thermal Protection Materials – Room Temperature to Their Upper Use Limit", AIAA 1996-1863, 31st Thermophysics Conference, Fluid Dynamics and Co-located Conferences.
- [16] Johnston, C. O., private communication, 2018-03-13
- [17] Rossman, G. A., "Conceptual Thermal Response Modeling, Testing, and Design of Flexible Heatshield Insulation Material", Thesis, Gerogia Institute of Technology, 2017.
- [18] Sudret, B., "Global Sensitivity Analysis Using Polynomial Chaos Expansion," *Reliability Engineering and System Safety*, Vol. 93, No. 7, 2008, pp. 964–979. <https://doi.org/10.1016/j.ress.2007.04.002>
- [19] Mahzari, M., Beck, R., Hwang, H., Monk, J., and Morgan, J., "Development and Sizing of the Mars 2020 Thermal Protection System," AIAA Paper 2022-3951, June 2022.