PROBABALISTIC RISK ANALYSIS AND THERMAL MARGIN PROCESS FOR AN INFLATABLE AEROSHELL

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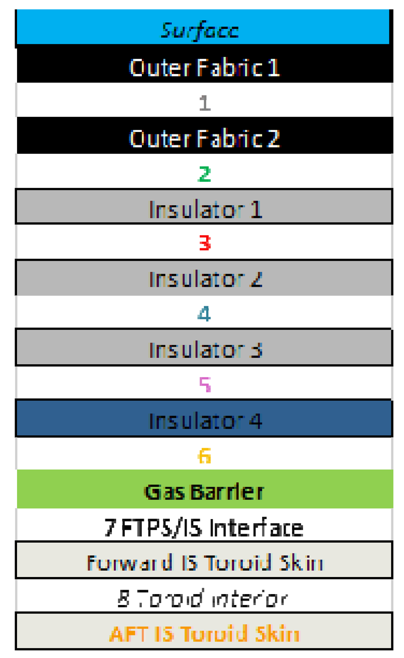
Low-Earth-Orbit Flight Test of an Inflatable Decelerator (LOFTID)

Abstract

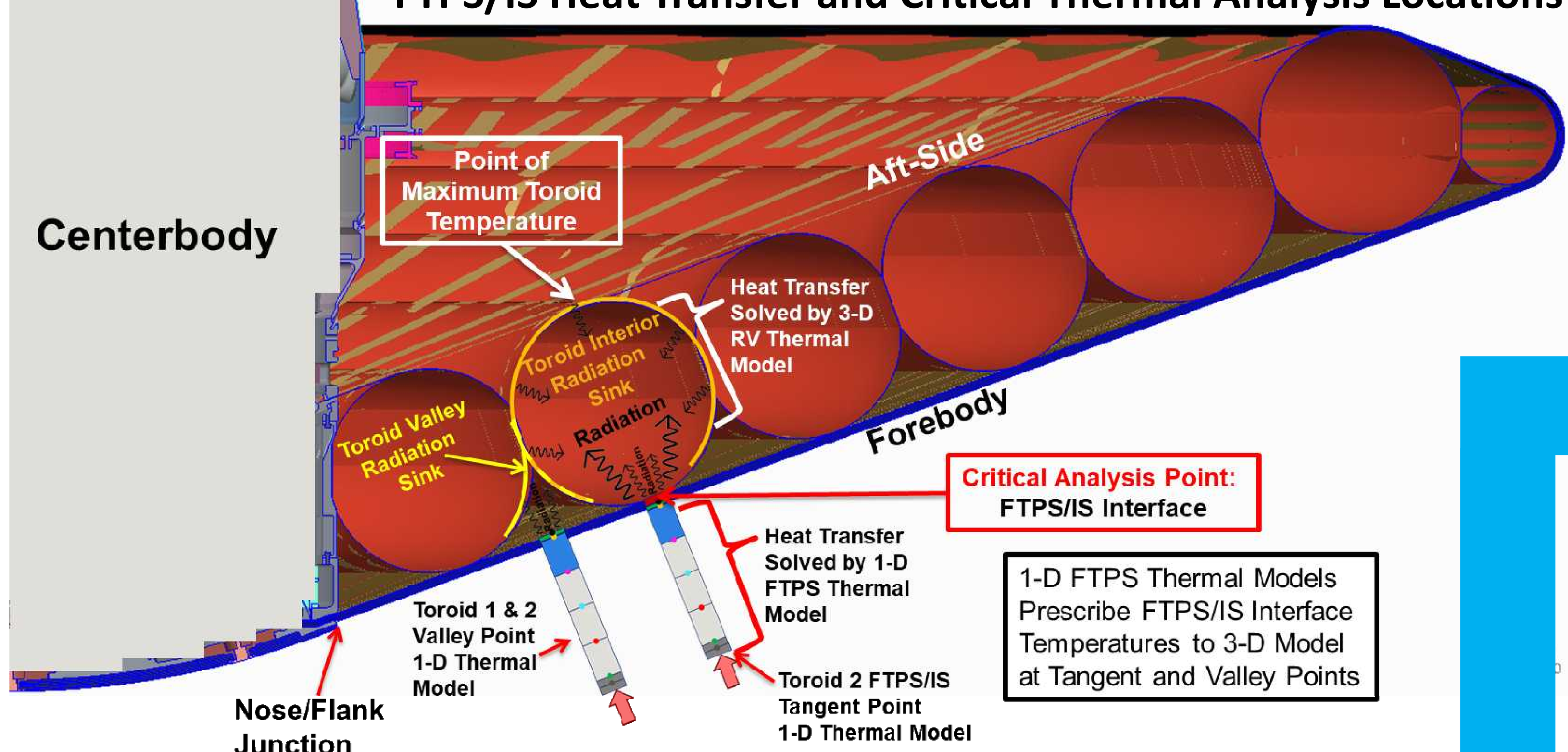
Atmospheric entry vehicle thermal protection systems (TPS) are margined due to the uncertainties that exist in entry aeroheating environments and the thermal response of the materials and structures. Traditional approaches typically over-margin TPS and offer very little insight into the risk of over-temperature during flight. A probabilistic margin process can be used to apply thermal margin to an aeroshell based on a rigorously calculated risk of failure. This probabilistic margin process allows engineers to make informed aeroshell design, entry-trajectory modifications, and risk trades while preventing excessive margin from being applied. This methodology can also be applied to other TPS applications, hot structures, and other engineering disciplines.

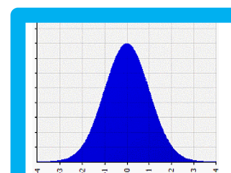


Flexible Thermal Protection System (FTPS) Layup over Inflatable Structure (IS)

LOFTID Aeroshell Structure

FTPS/IS Heat Transfer and Critical Thermal Analysis Locations



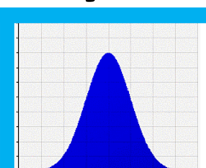


End-to-End Monte Carlo Uncertainty Propagation Approach

Structured Set of Dispersed Uncertain Input Parameters

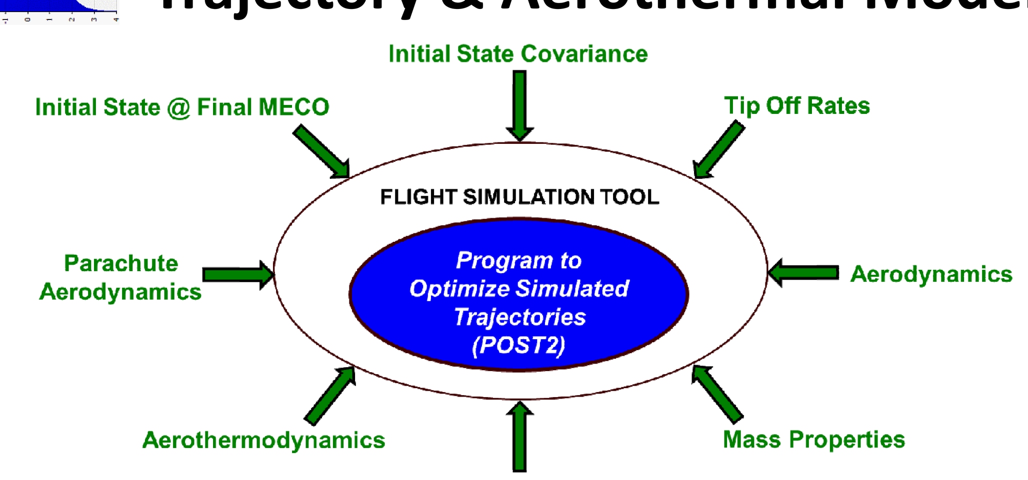
$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}$$

- 2000 samples generated for a total of 74 uncertain input parameters
- Each sample corresponds to a unique trajectory given a set of trajectory, aerothermal, and thermal model uncertain inputs:
  - 58 uncertainties in the trajectory model
  - 3 uncertainties in the forebody and aftbody aerothermal indicators
  - 13 uncertainties in the thermal model



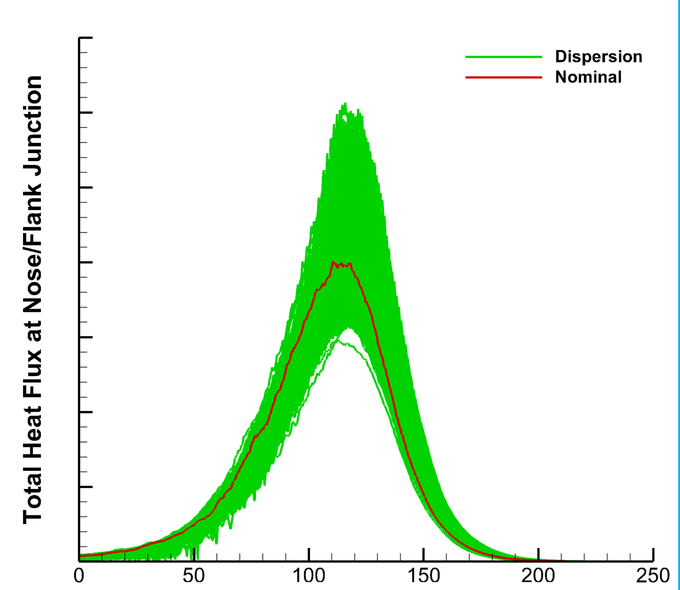
Monte Carlo #1

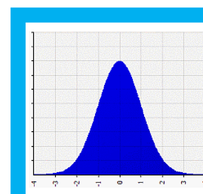
Trajectory & Aerothermal Models



INPUTS:
- Forebody and aft-Side aeroheating indicators (function of density, velocity, and angle of attack)

OUTPUTS:
- Dispersions of entry aeroheating and surface pressure profiles



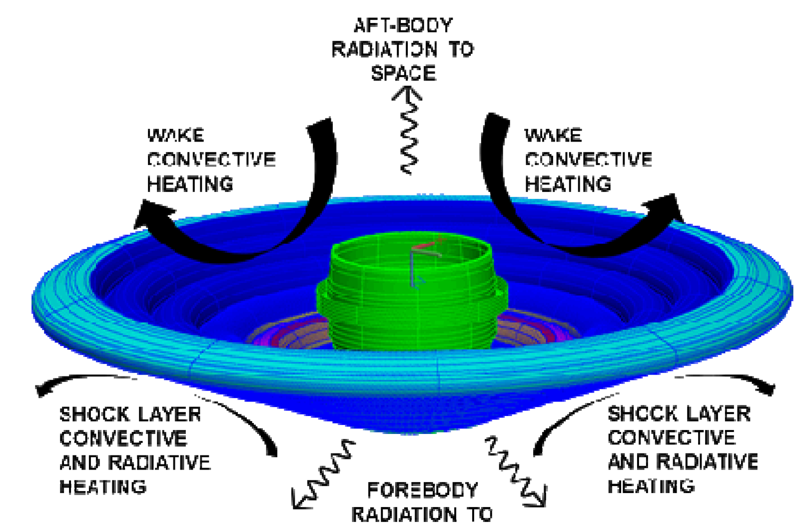


Monte Carlo #2

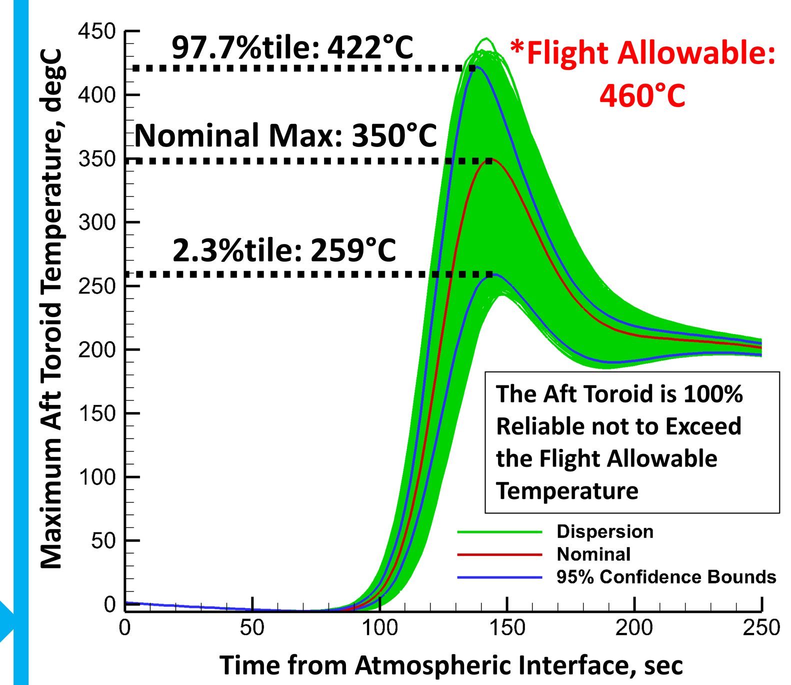
Reentry Vehicle (RV) Thermal Model

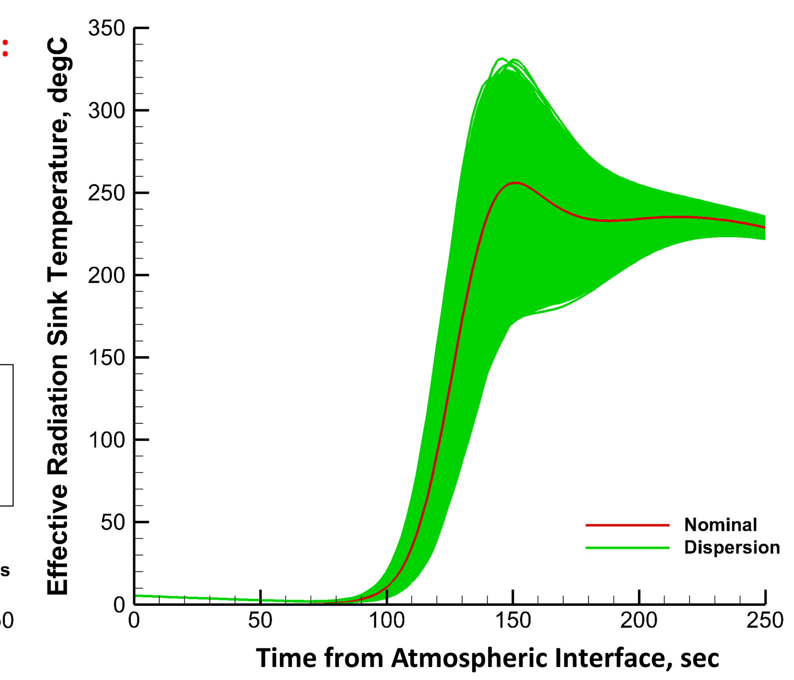
INPUTS:
- Dispersed aft-Side surface heating parameters due to wake flow convective heating
- Fixed FTPS/IS interface temperature boundary condition

OUTPUTS:
- Dispersions of aft-Side toroid skin temperature vs. time profiles
- Maximum aft-Side toroid skin temperature probability distribution

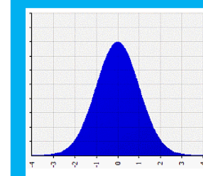


3-D RV Thermal Model in Thermal Desktop with External Heating Drivers



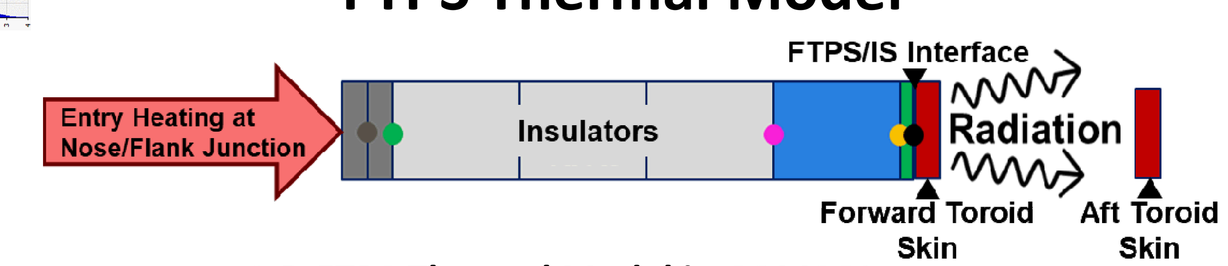


	FTPS/IS Interface	Aft Toroid Skin
Limit	400°C	480°C
Safety Delta	5°C	20°C
Flight Allowable	395°C	460°C



Monte Carlo #3

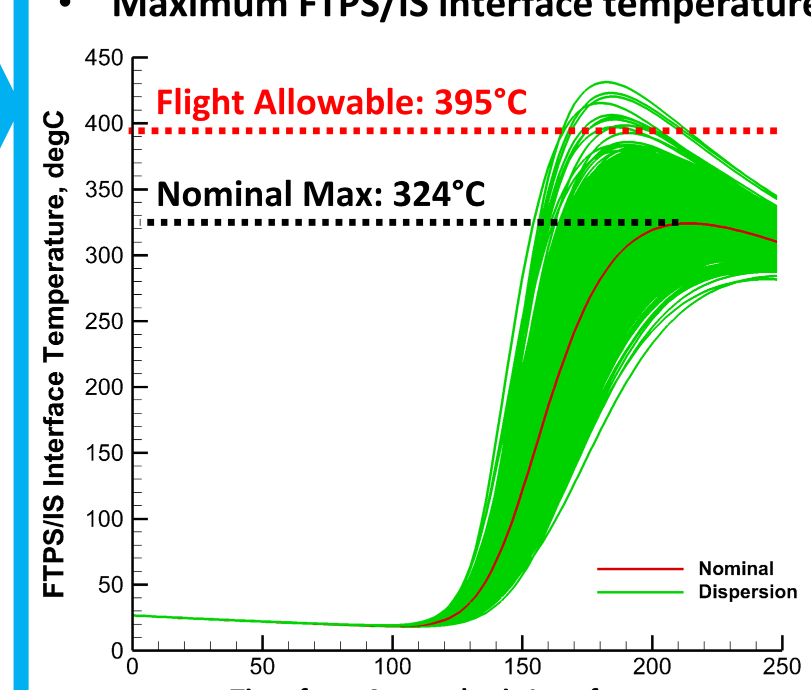
FTPS Thermal Model

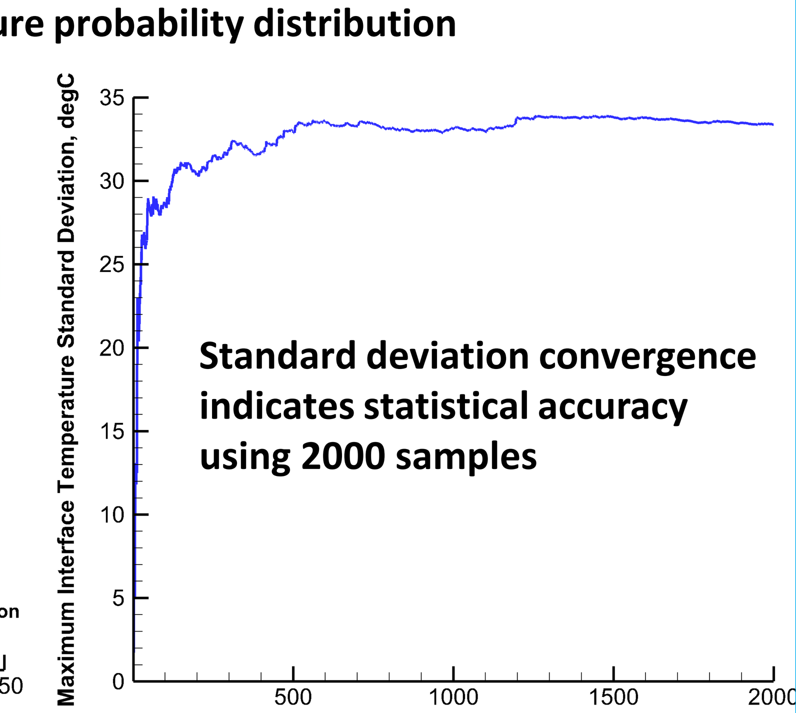


1-D FTPS Thermal Model in COMSOL

INPUTS:
- Dispersed aeroheating parameters vs time profiles at nose/flank junction
- Dispersed surface pressure vs time profiles
- Dispersed aft-side toroid skin temperature vs. time profiles (effective toroid interior radiation sink temperature boundary condition)

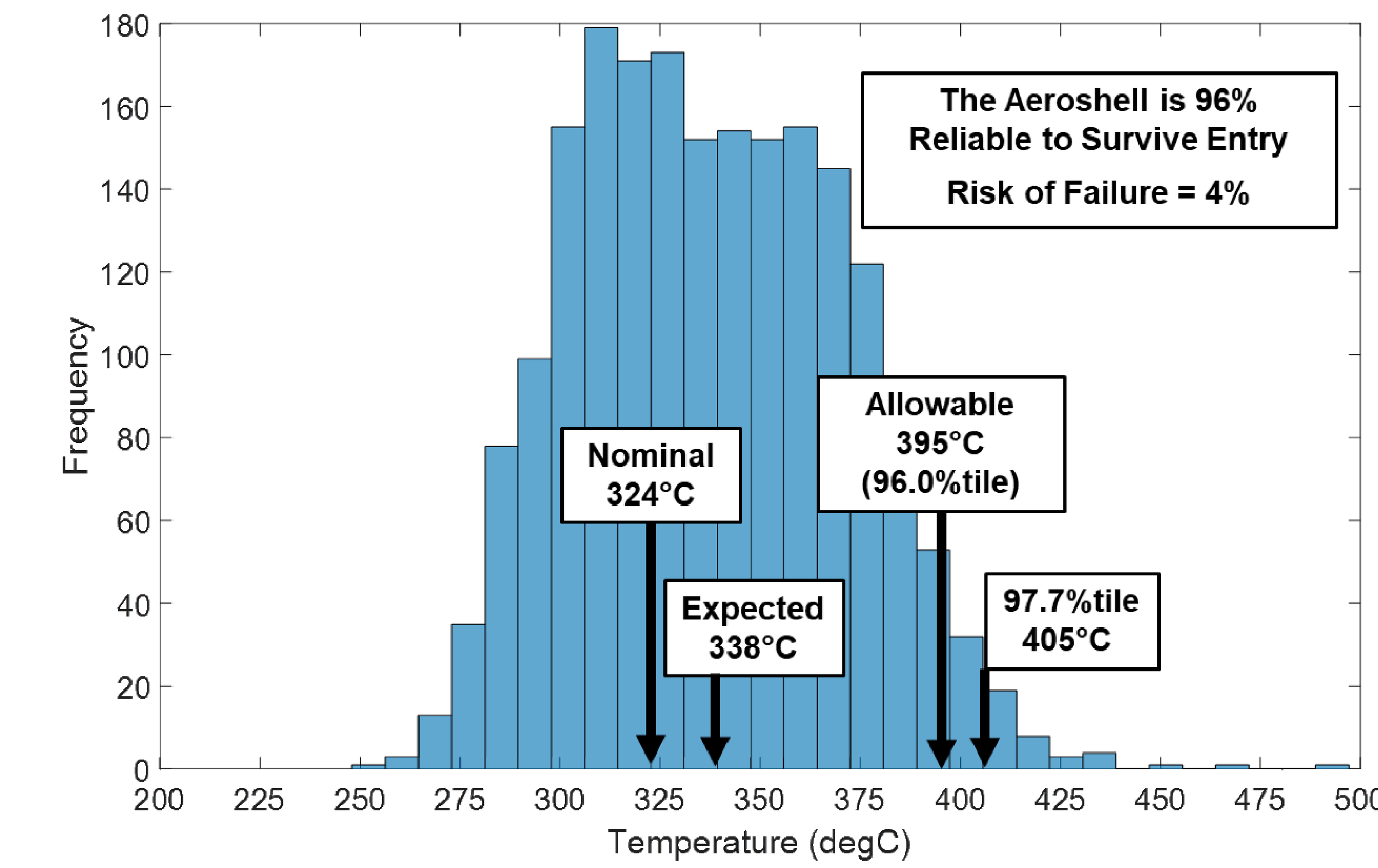
OUTPUTS:
- Dispersions of FTPS/IS interface temperature vs time profiles
- Maximum FTPS/IS interface temperature probability distribution



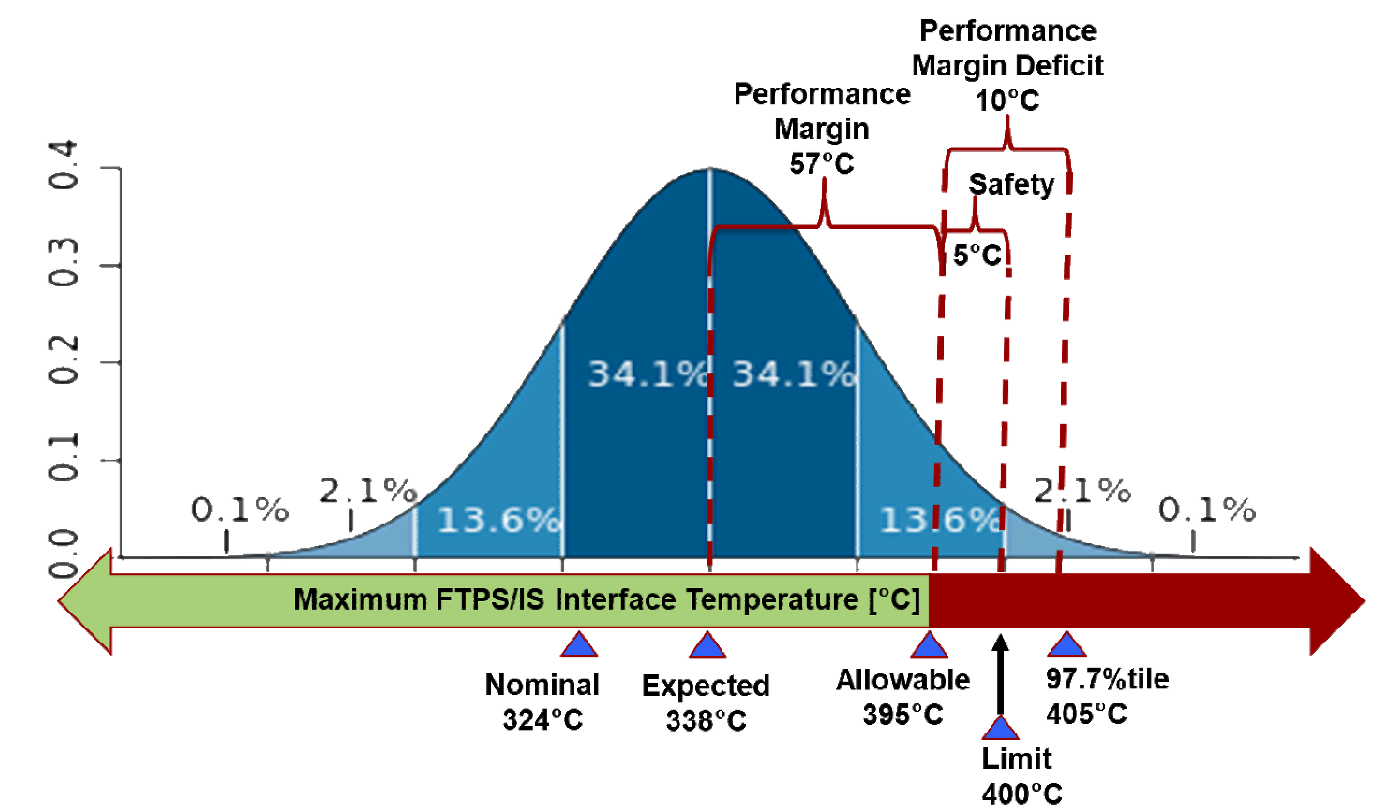


End-to-End Monte Carlo Results:

Aeroshell Risk and Thermal Margin Assessment



2000 Sample Histogram of Maximum FTPS/IS Interface Temperature



Probabilistic Thermal Margin Definitions

Conclusions

The presented probabilistic thermal margin process informs mitigations needed to satisfy LOFTID's aeroshell reliability standard. The uncertainty analysis shows that there is high confidence that the aft-side toroid skin, subject to wake convective heat loads, will not exceed flight allowable temperatures. However, the uncertainty analysis also shows that the aeroshell is 96% reliable to survive atmospheric entry based on the calculated probability of the FTPS/IS interface exceeding its flight allowable temperature. Because the current risk of aeroshell failure falls short of satisfying the project's reliability standard, several mitigation options are recommended, including a combination of adjustments to the entry trajectory and reduction of conservative assumptions in the thermal models.