



Low-Earth Orbit Flight Test
of an Inflatable Decelerator

National Aeronautics and
Space Administration



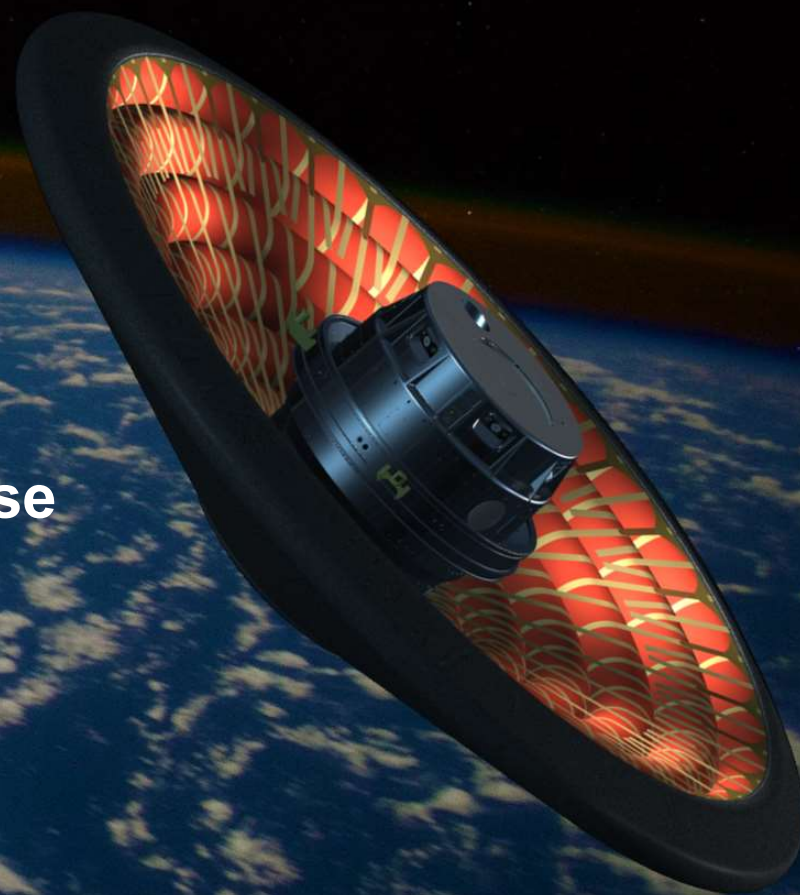
Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID)

Probabilistic Aeroshell Thermal Response Uncertainty Analysis

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Introduction



➤ Background

- Since the LOFTID project is an experimental technology demonstration, it was desired to drive the aeroshell in the reentry environment to temperatures that adequately prove the technology and validate the thermal response models, at an acceptable risk

➤ Objective

- Make informed aeroshell design, flight design, and flexible thermal protection system (FTPS) performance reliability trades while preventing excessive margin
- Probabilistic uncertainty analysis informs design and risk for a specific project reliability requirement
 - Aeroshell heat load capacity and flight heat load target driven by initial entry state
 - FTPS size and required thermal margin
 - Risk of aeroshell exceeding flight allowable temperatures

➤ Approach

- Probabilistic uncertainty analysis is carried out using an end-to-end Monte Carlo process where three separate Monte Carlo simulations are sequentially run:
 - Entry trajectory/aerothermal model, reentry vehicle (RV) thermal model, FTPS thermal model
 - Uncertainties in the trajectory and aeroheating model are propagated into the FTPS and RV thermal models to quantify the resulting probability distribution of the aeroshell thermal response



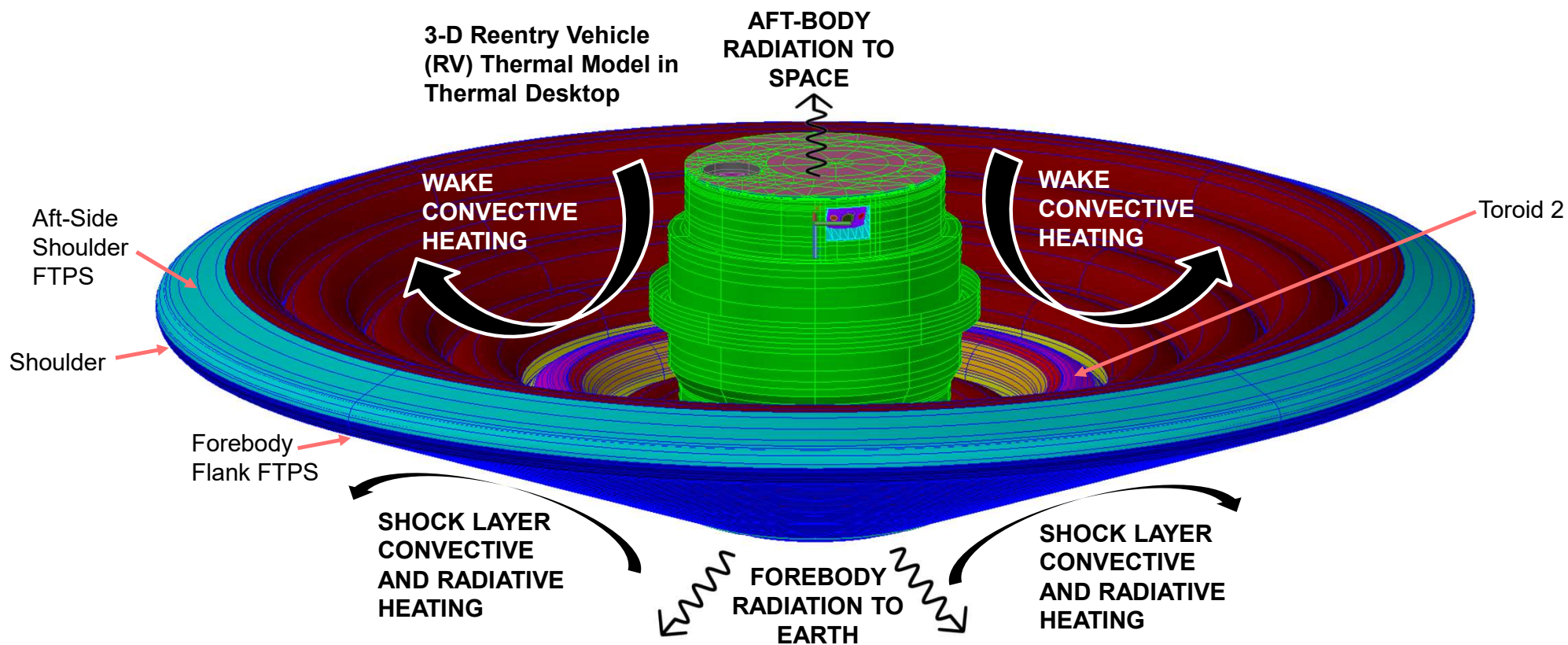
Aeroshell Thermal Response Modeling





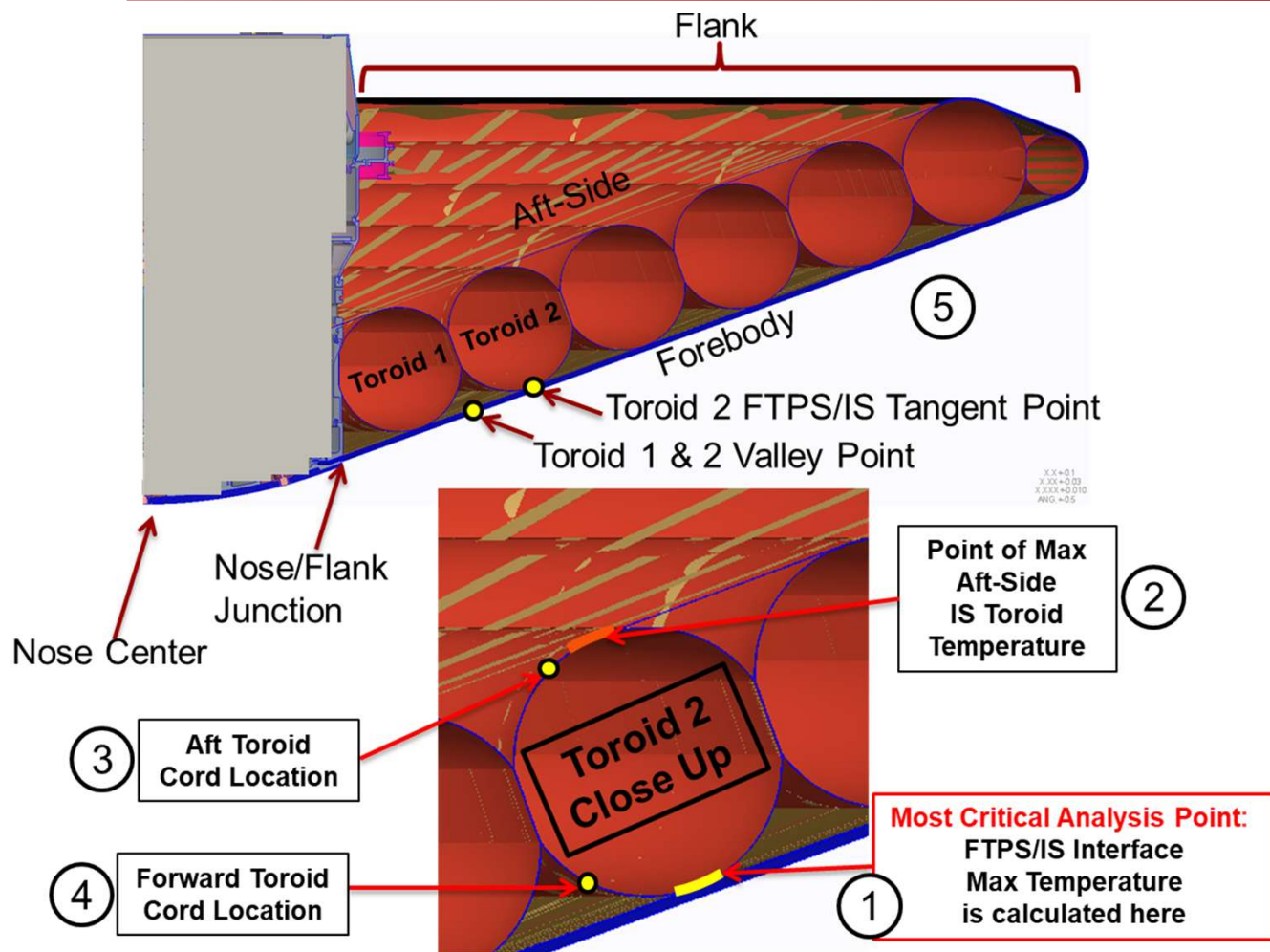
LOFTID 3-D Reentry Vehicle (RV) Thermal Model

Reentry Thermal Energy Balance





Critical Aeroshell Points for Thermal Response Analysis and FTPS Sizing



Flank FTPS Layup

Surface
Outer Fabric 1
1
Outer Fabric 2
2
Insulator 1
3
Insulator 2
4
Insulator 3
5
Insulator 4
6
Gas Barrier
7 FTPS/IS Interface
Forward IS Toroid Skin
8 Toroid Interior
AFT IS Toroid Skin

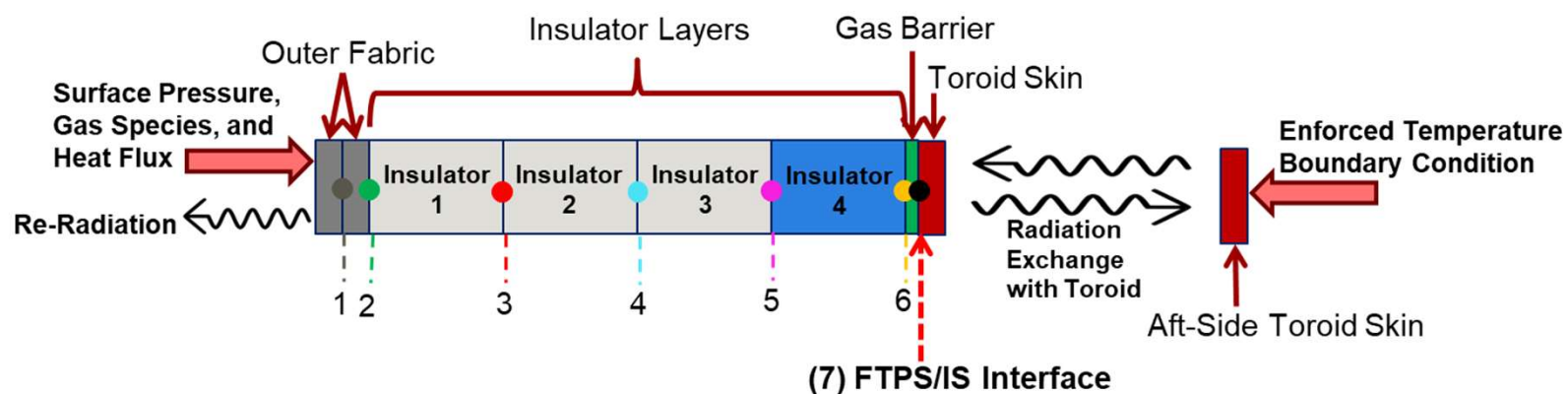


1-D Flexible Thermal Protection System (FTPS) Thermal Model Overview



➤ Model Components and Boundary Conditions

1-D FTPS Model in COMSOL - Finite Element Heat Transfer Solver



➤ Model Objectives

- Solve the temperature distribution through the FTPS at various points on the aeroshell during atmospheric reentry
- Solve the maximum FTPS/IS interface temperature
- Solve the maximum outer fabric temperature
- Solve the maximum gas barrier temperature

➤ Model Timeline

- FTPS heat transfer simulation is initialized at atmospheric interface (125 km)
- Regular simulations run until parachute deployment
- Monte Carlo simulation sample simulations run through the bulk of the heat pulse until Mach 0.7 to capture Max FTPS/IS Interface temperature



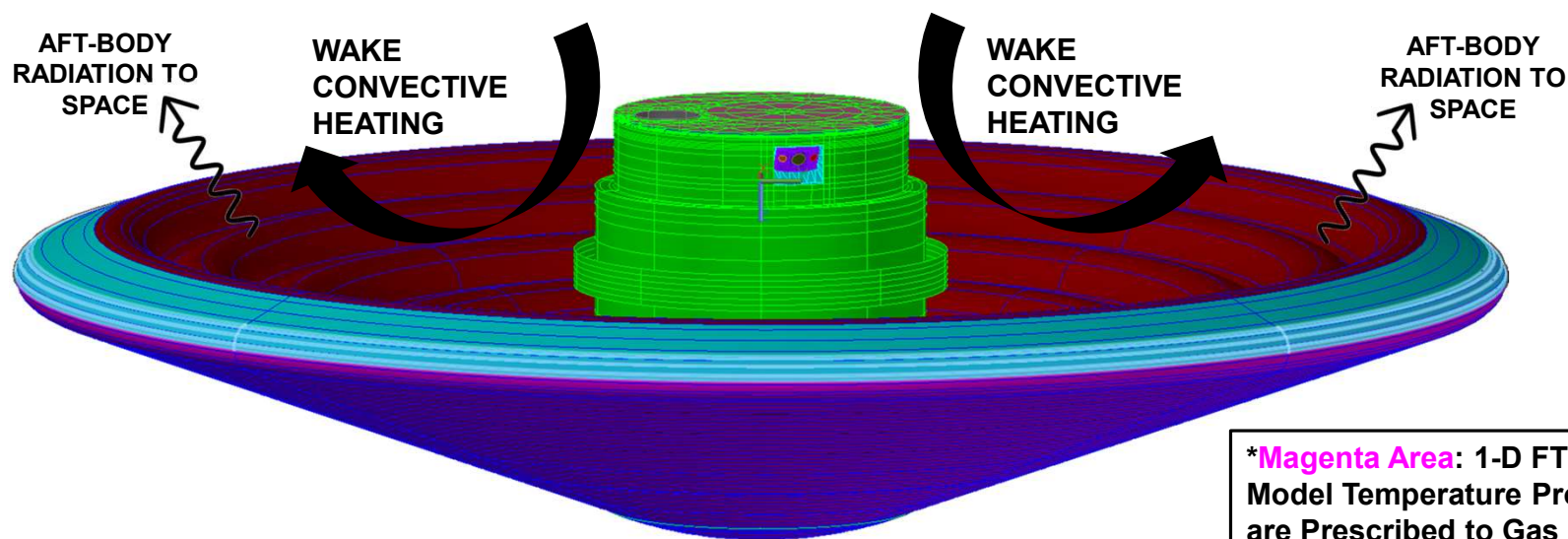
1-D FTPS and 3-D Aeroshell Model Coupling

➤ Forebody Boundary Condition

- Gas Barrier Temperature is prescribed from 1-D FTPS Thermal Model results (COMSOL)

➤ Aft-Side Boundary Conditions

- Wake convective heating loads are spatially distributed on the inflatable structure and calculated based on heat transfer coefficient solutions from MAP/LAURA/FUN3D CFD analysis
 - Peak wake convective heating is centered on Toroid 2
- The inflatable structure radiates to space and receives solar heating





Probabilistic Thermal Margin Process

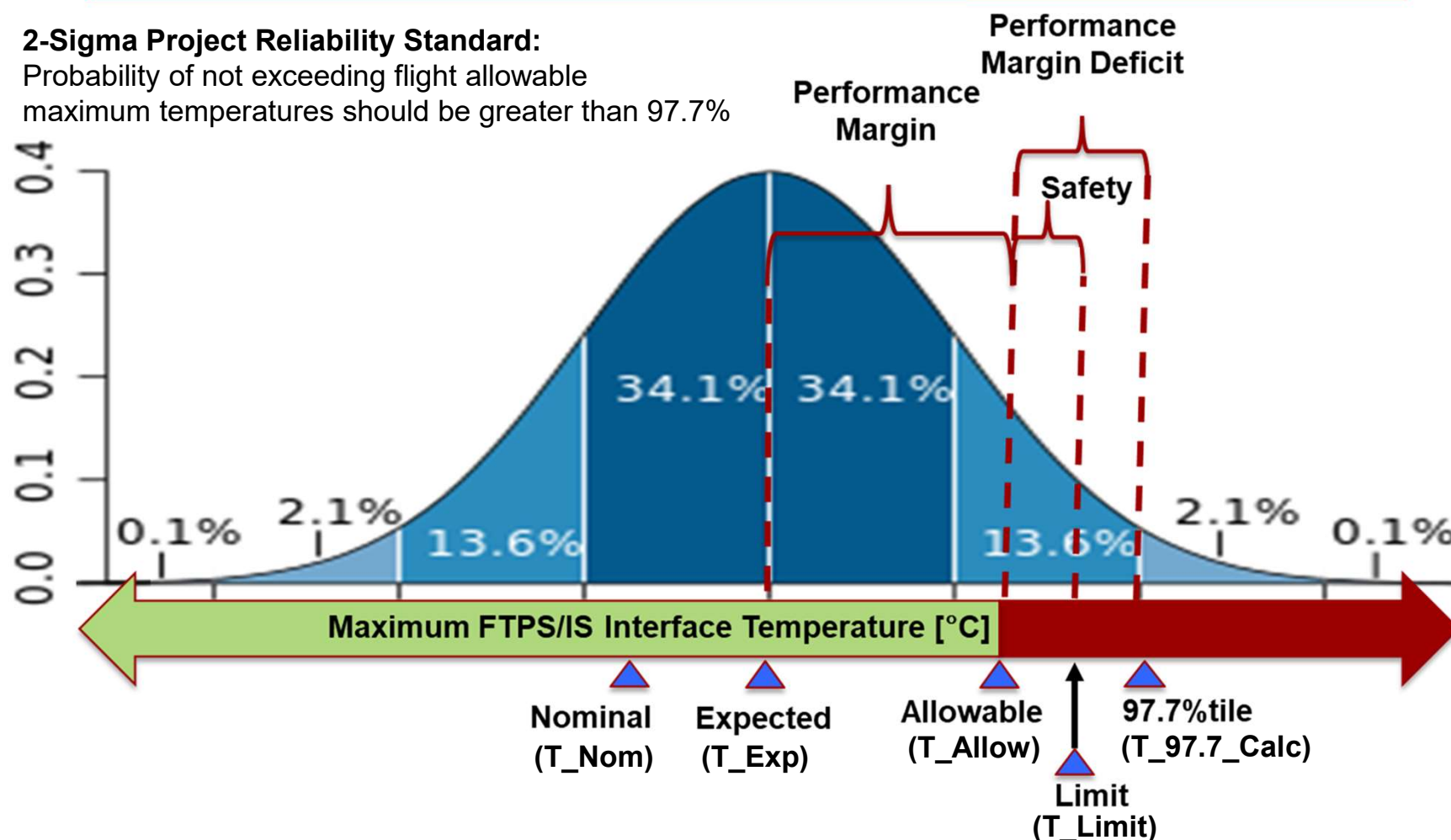




Probabilistic Thermal Margin Parameter Definitions

2-Sigma Project Reliability Standard:

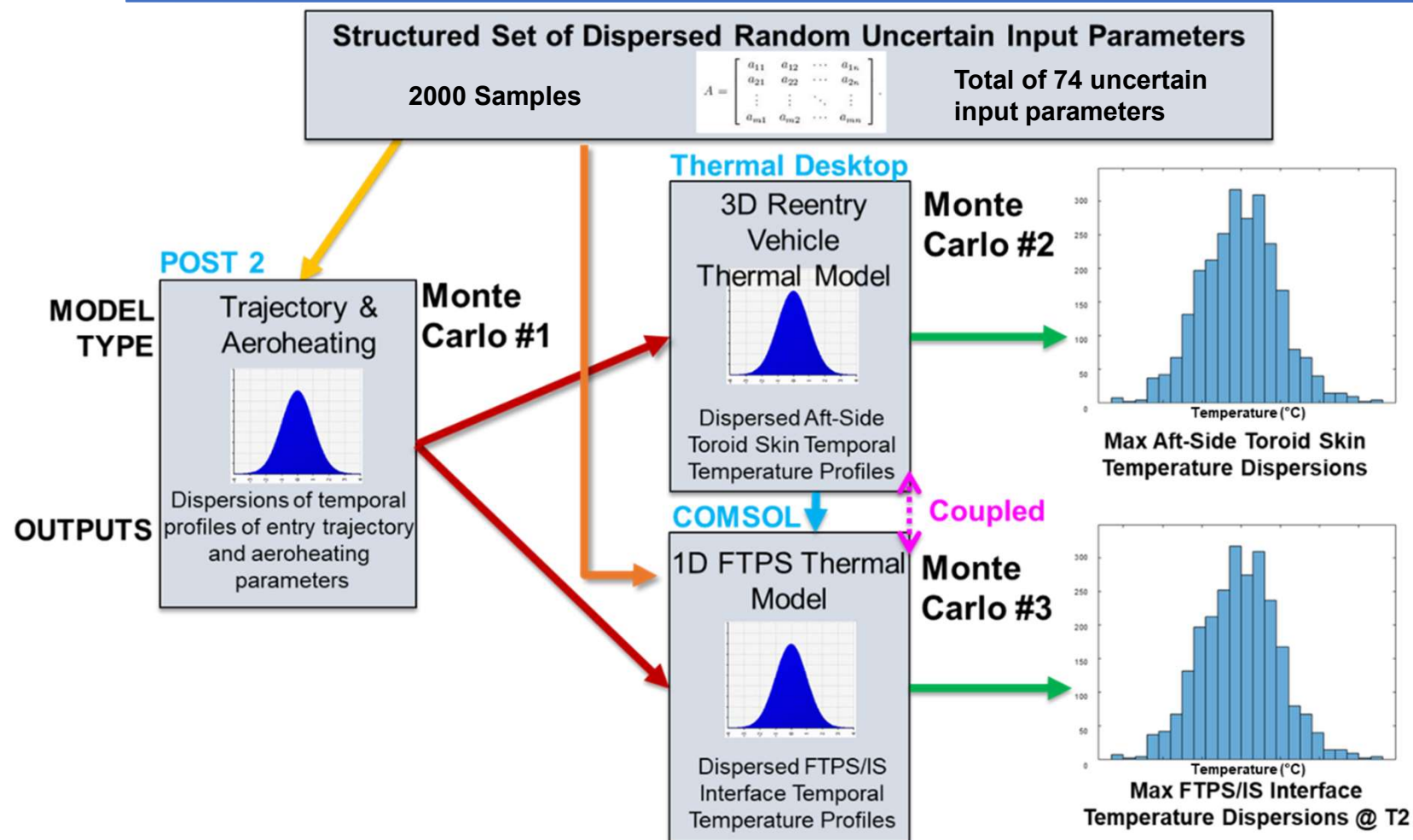
Probability of not exceeding flight allowable maximum temperatures should be greater than 97.7%





End-to-End Monte Carlo Simulation Overview

Aeroshell Thermal Response Probabilistic Uncertainty Analysis





Dispersed Uncertain Input Parameters



Discipline	Parameter Name/Type
Trajectory (58)	Initial Entry State (6)
	Roll/Tip-Off Rates (5)
	Mass Properties (10)
	Attitude (3)
	Aerodynamics (34)
Aerothermodynamics (3)	Forebody Convective Heat Transfer Coefficient Multiplier
	Forebody Radiative Heating Multiplier
	Wake Convective Heating Multiplier
Thermal Response (13)	Thermal Conductivity of Outer Fabric Multiplier
	Thermal Conductivity of Insulator 1-3 Multiplier
	Thermal Conductivity of Insulator 4 Multiplier
	Specific Heat of Outer Fabric Multiplier
	Specific Heat of Insulator 1-3 Multiplier
	Specific Heat of Insulator 4 Multiplier
	Activation Energy for Insulator 1-3 Decomposition Multiplier
	Activation Energy for Insulator 4 Decomposition Multiplier
	Gas Thermal Conductivity for Insulator 1-3 Multiplier
	Gas Thermal Conductivity for Insulator 4 Multiplier
	Emissivity of Outer Fabric Adder
	Slope of Emissivity of Outer Fabric above 1373 K Adder
	FTPS/IS Max Interface Temperature Bias Multiplier

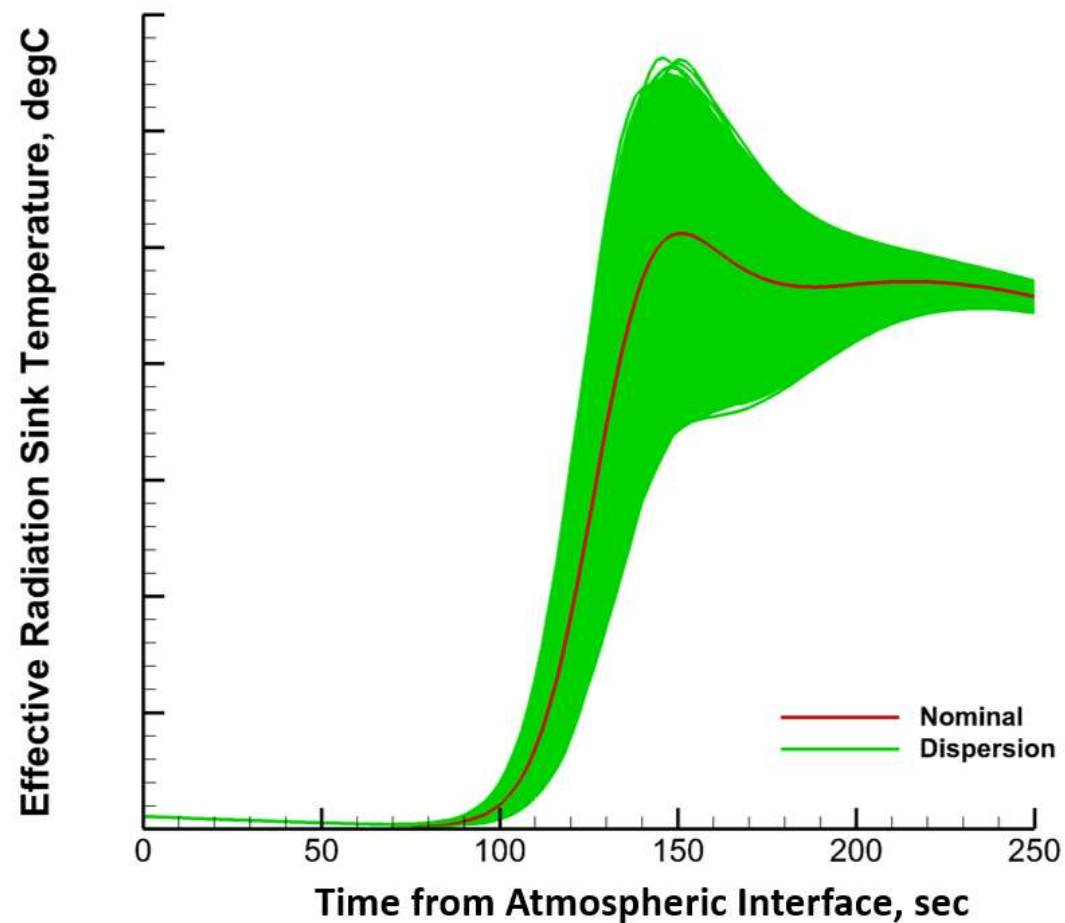
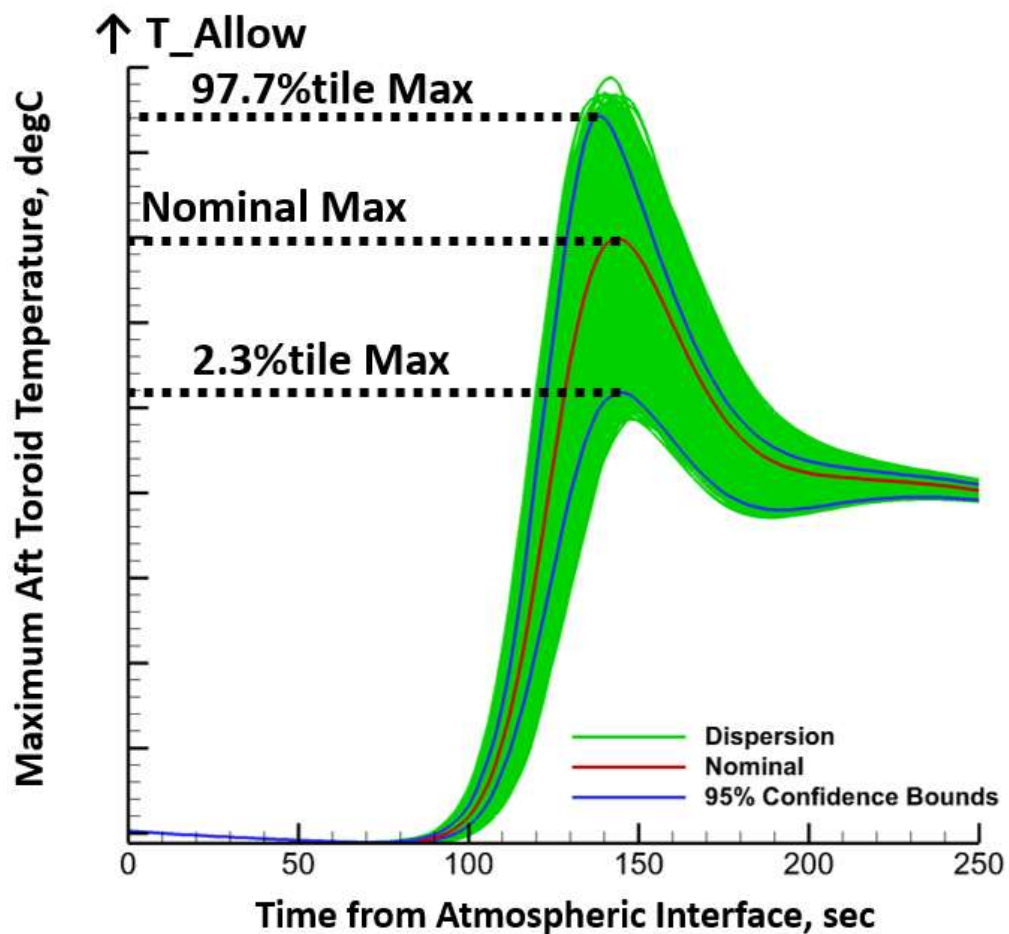


Probabilistic Uncertainty Analysis Results





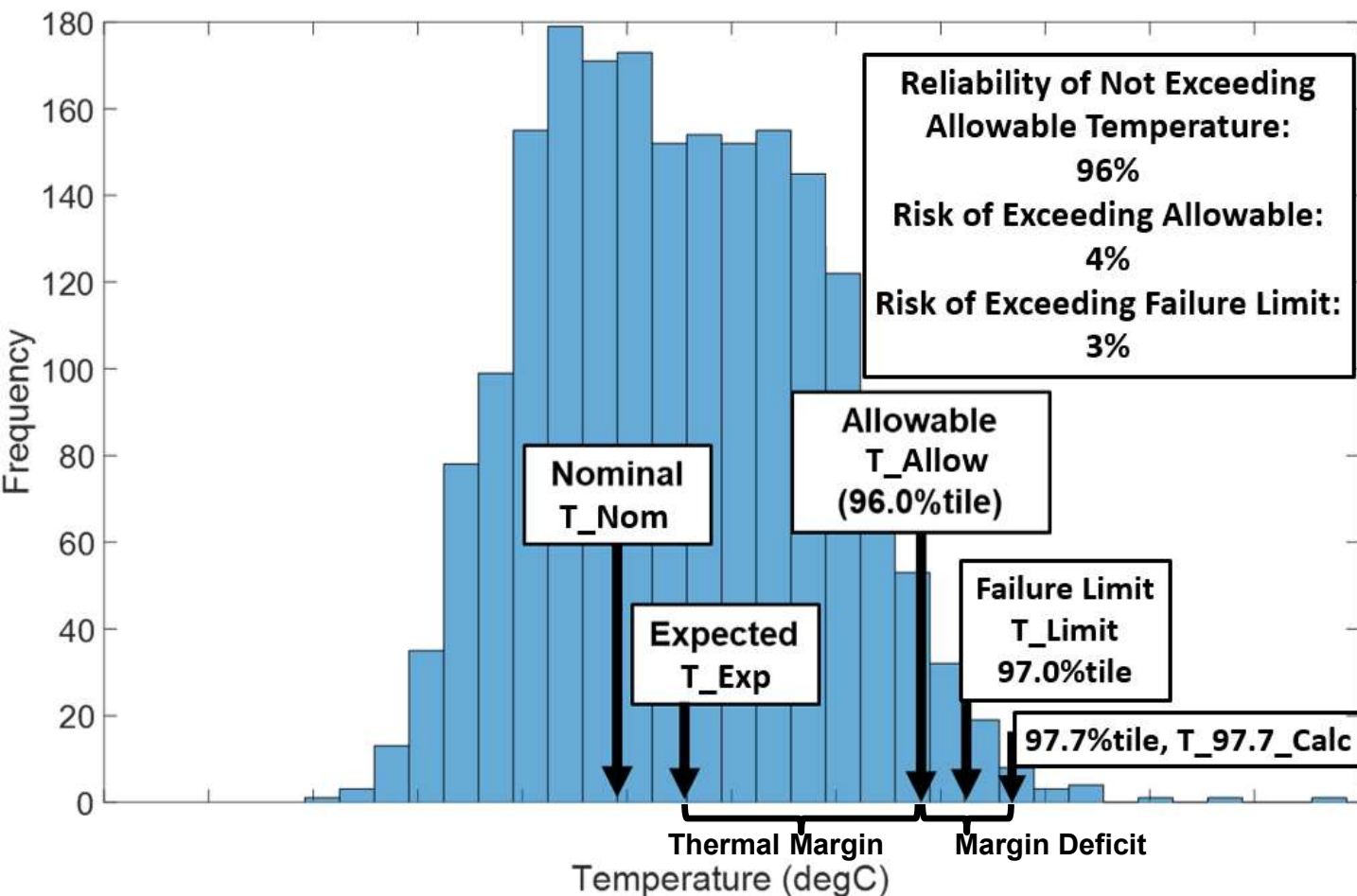
Monte Carlo #2 Example Results Maximum Aft-Side Temperature Profile Dispersions





Monte Carlo #3 Example Results

2000 Sample Histogram of Maximum FTPS/IS Interface Temperature

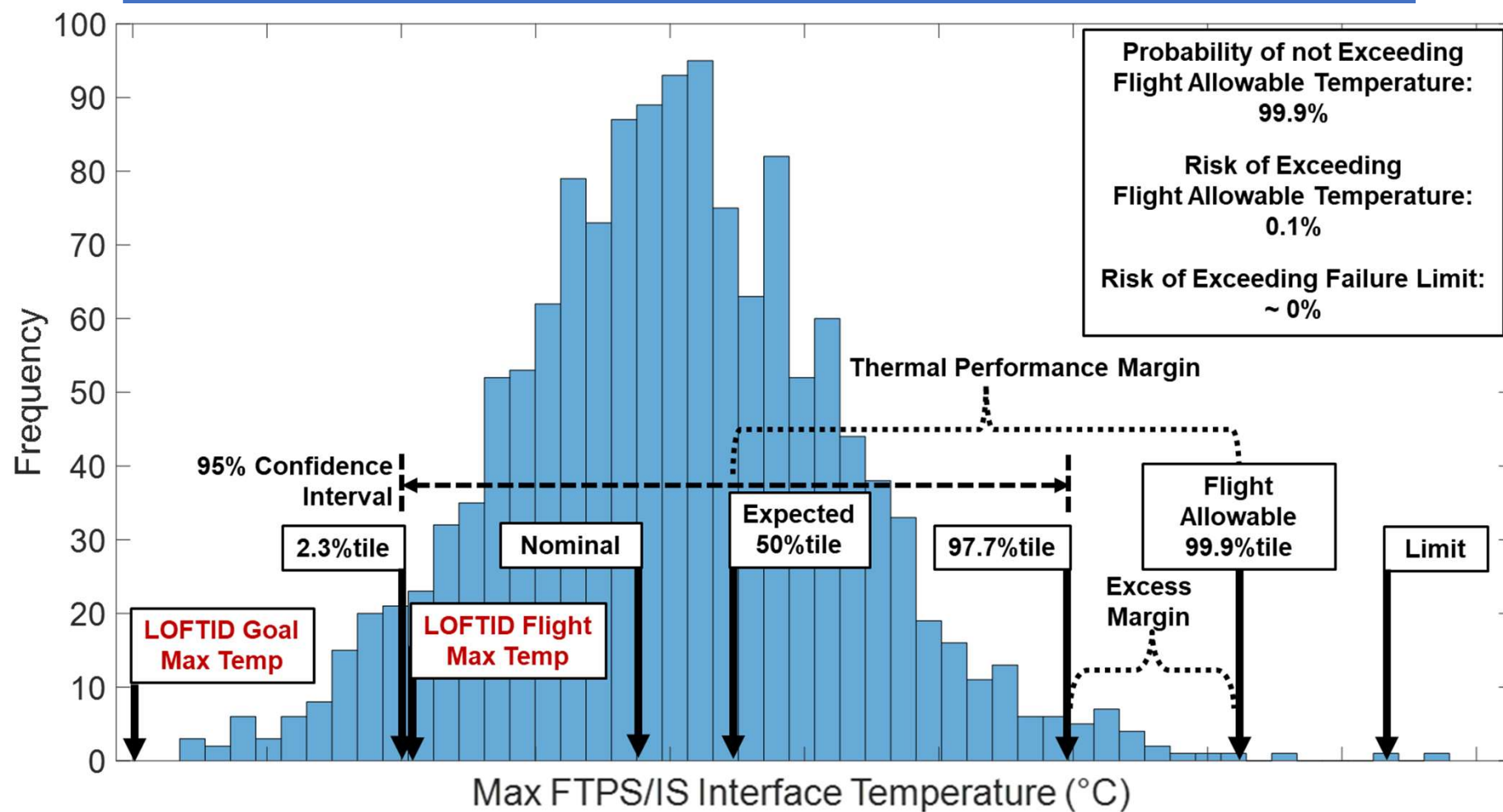


To Eliminate Margin Deficit:

1. Tailor the initial entry state of the reentry vehicle to lower the resultant entry heat load
 - Entry Mass
 - Entry Velocity
 - Entry Flight Path Angle
2. Reduce Conservatisms in Thermal Models
 - Higher Fidelity
 - Testing and Correlation
3. Material property tests to reduce the uncertainty
4. Increase FTPS Thickness



Pre-Flight LOFTID Results

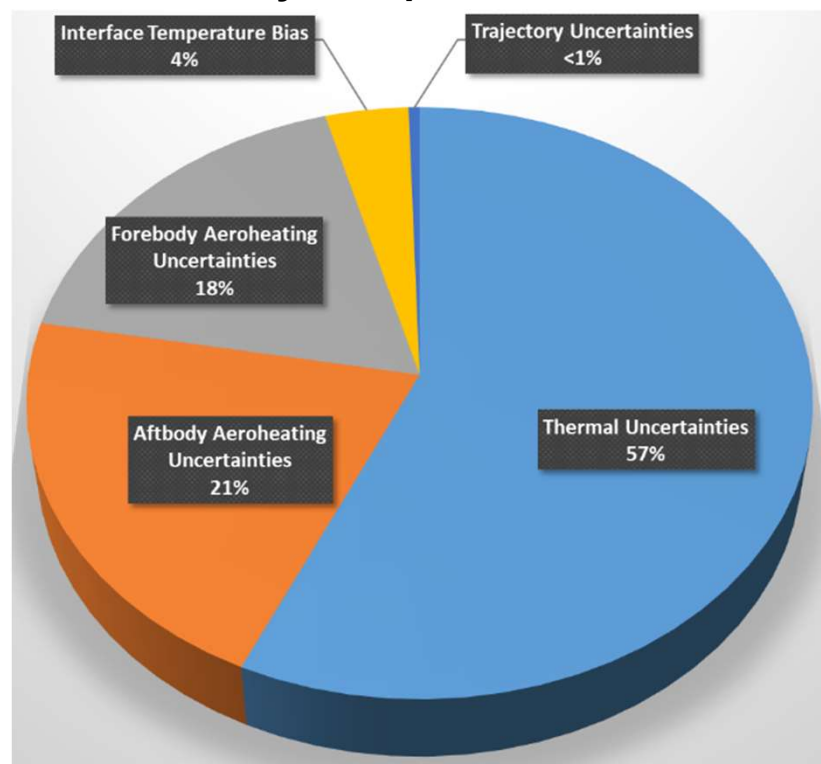




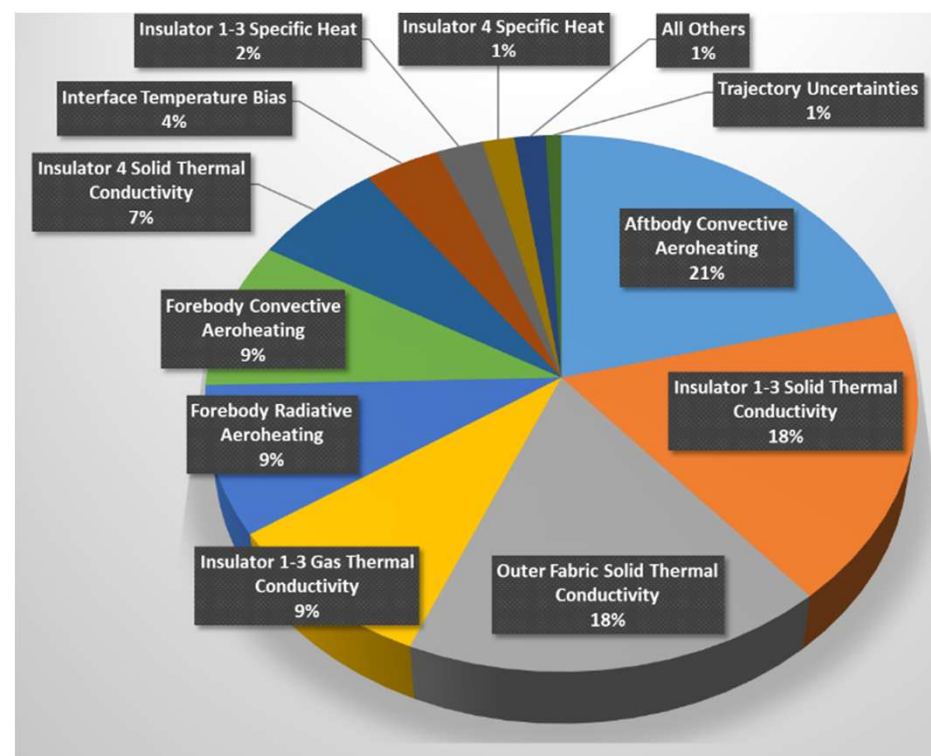
Max FTPS/IS Interface Temperature Uncertainty Sensitivity Breakdown



Breakdown by Discipline:



Breakdown by Property:



- A sensitivity analysis was performed using a Sobol indice approach
- Material thermal and aeroheating uncertainties significantly outweigh trajectory and model error uncertainties
- The top four contributors which make up 75% of the influence on the overall max FTPS/IS interface temperature variance are aftbody aeroheating, total forebody aeroheating, thermal conductivity of insulator layers 1-3, and the outer fabric thermal conductivity



Summary and Conclusions



- **The probabilistic thermal margin process is a departure from the traditional RSS approach of combining conservatively bounding-case entry-trajectory and aeroheating environments to drive FTPS sizing**
 - A study showed that the RSS method would have called for at least 26% more FTPS insulation
- **The probabilistic uncertainty analysis results informed mitigations needed to achieve acceptable thermal performance reliability without applying unnecessary margin which would be counterproductive for a technology demonstration mission.**
 - The process allowed for more informative risk and design trades to drive strategic atmospheric entry trajectory parameter selection
- **A 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 for future EDL applications**
 - FTPS was sized and entry trajectory designed with adequate but not overly conservative margin
 - The hottest point on the inflatable structure exceeded the minimum project goal
 - No in-flight failures due to thermal overload