Towards Flight Uncertainty Prediction of Hypersonic Entry Systems

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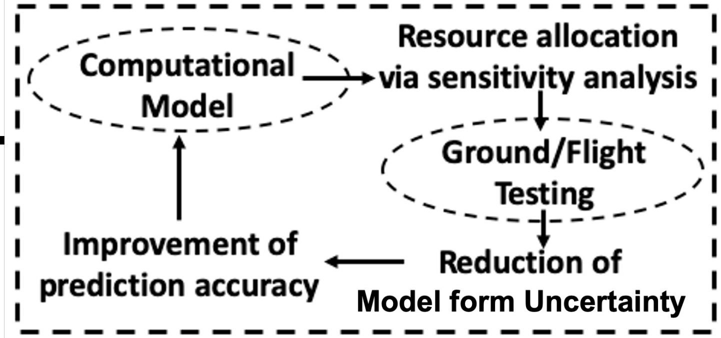
Outline

- **Motivation for Aerothermal Uncertainty Quantification**
- **Flight Uncertainty Prediction Approach**
- **Model Input Uncertainty Quantification Approach**
- **Aerothermal Uncertainty Quantification Applications**
  - **Stagnation point heat flux prediction of a hypersonic vehicle with a reduced order correlation**
  - **Thermal Protection System Response of a Hypersonic Inflatable Aerodynamic Decelerator**
- **Conclusions**

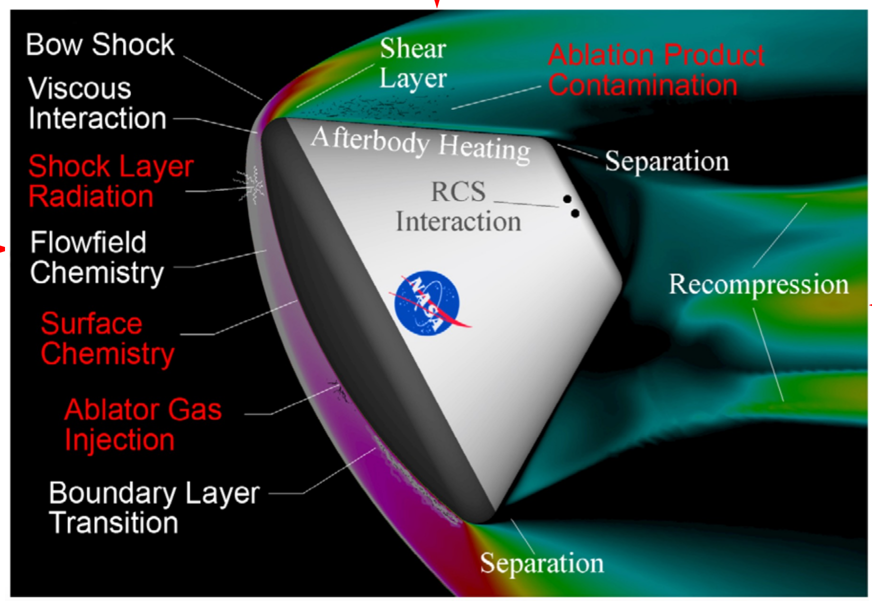
Integrating Uncertainty Quantification to Planetary Entry Systems Modeling and Simulation

Model Prediction Accuracy Improvement



Evaluation of performance under uncertain operating conditions and model uncertainties

Flight Performance Prediction



Increase Robustness and Survivability

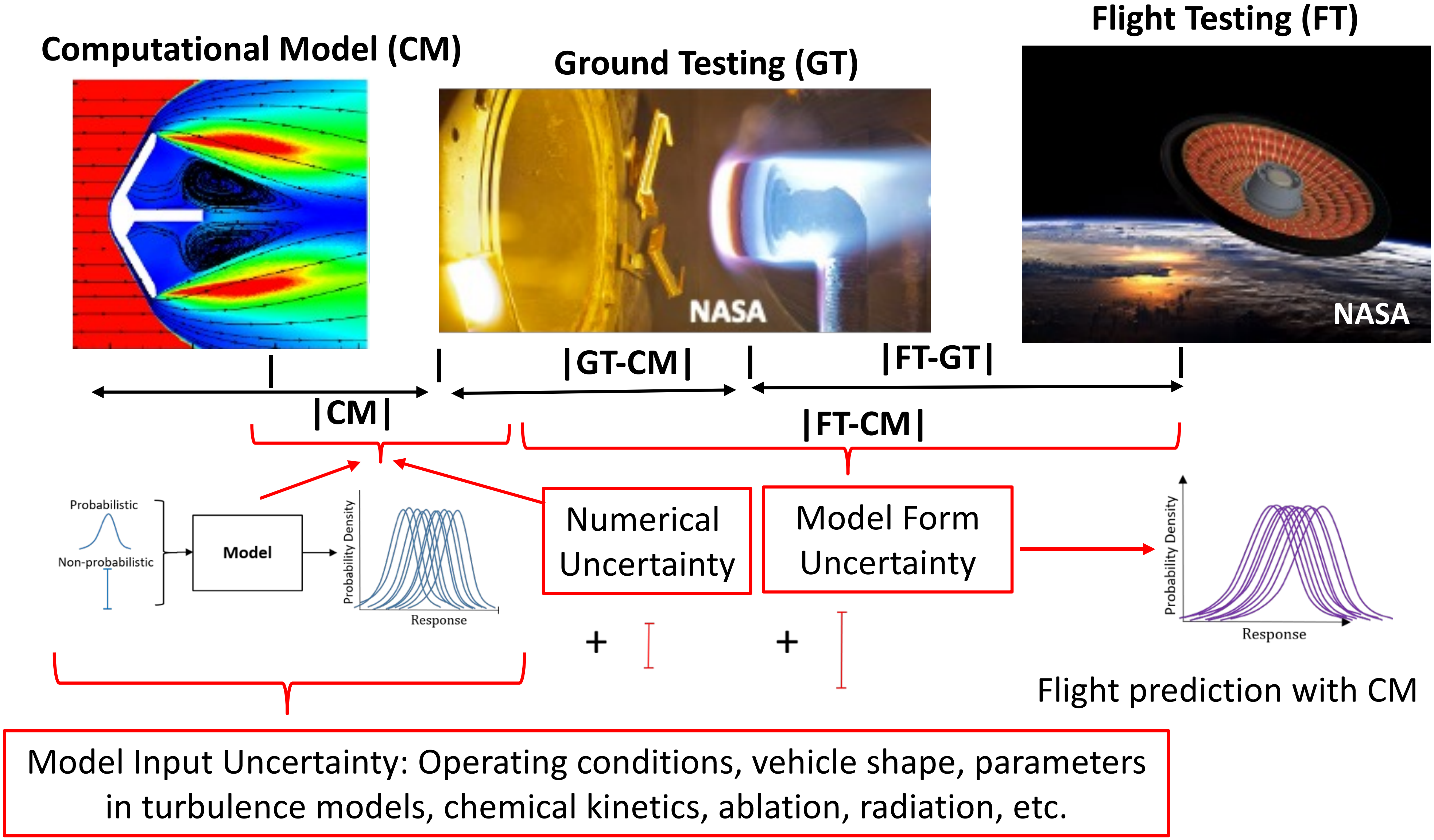
Reduce the impact of uncertainties on vehicle performance and reliability

Quantification of Margins and Uncertainties

Flight Qualification with Modeling

Refs [1, 2]

Physics-Based Flight Performance Uncertainty Prediction with Computational Models



Challenges for Aerothermal Uncertainty Quantification

- Significant computational cost for high-fidelity aerothermal modeling
  - Monte Carlo not feasible
  - ➢ Utilize stochastic surrogates based on polynomial chaos

- Need a non-intrusive approach so that the computational models (CFD) require no major modification
  - ➢ Utilize non-intrusive polynomial chaos (NIPC) [3]

- Large number of uncertain variables
  - ➢ Utilize effective global non-linear sensitivity analysis (Sobol indices calculated from PC expansion) for dimension reduction
  - ➢ Utilize Sparse Sampling NIPC [4,5]

- Mixed (aleatory + epistemic) uncertainty propagation
  - ➢ Utilize nested uncertainty propagation with PC surrogates [6]

Sensitivity and Uncertainty Quantification Approach

Stochastic response surface based on polynomial chaos expansion

$$\alpha^*(\mathbf{x}, \boldsymbol{\xi}) \approx \sum_{i=0}^{P} \alpha_i(\mathbf{x}) \Psi_i(\boldsymbol{\xi})$$

$\alpha_i(\mathbf{x})$: Deterministic Component (expansion coefficients)

$\Psi_i(\boldsymbol{\xi})$: Random Basis Functions (orthogonal polynomials)

- Point-Collocation NIPC: Choose N_s samples to evaluate the deterministic model

$$\begin{pmatrix} \alpha^*(\boldsymbol{x}, \boldsymbol{\xi}_0) \\ \alpha^*(\boldsymbol{x}, \boldsymbol{\xi}_1) \\ \vdots \\ \alpha^*(\boldsymbol{x}, \boldsymbol{\xi}_{(N_s-1)}) \end{pmatrix} = \begin{pmatrix} \Psi_0(\boldsymbol{\xi}_0) & \Psi_1(\boldsymbol{\xi}_0) & \dots & \Psi_P(\boldsymbol{\xi}_0) \\ \Psi_0(\boldsymbol{\xi}_1) & \Psi_1(\boldsymbol{\xi}_1) & \dots & \Psi_P(\boldsymbol{\xi}_1) \\ \vdots & \vdots & \ddots & \vdots \\ \Psi_0(\boldsymbol{\xi}_{(N_s-1)}) & \Psi_1(\boldsymbol{\xi}_{(N_s-1)}) & \dots & \Psi_P(\boldsymbol{\xi}_{(N_s-1)}) \end{pmatrix} \begin{pmatrix} \alpha_0 \\ \alpha_1 \\ \vdots \\ \alpha_P \end{pmatrix}$$

$(N_s \, x \, 1)$ $(N_s \, x \, N_t)$ $(N_t \, x \, 1)$

- the total number of output modes (terms in the expansion), N_t

$$N_t = P + 1 = \frac{(n+p)!}{n!p!}$$

p : polynomial order of total expansion

n : number of uncertain variables

Sensitivity and Uncertainty Quantification Approach

- When $N_s = N_t$: minimum number of samples required to obtain a solution with the determined system (coefficient vector)

- When $N_s > N_t$: Overdetermined system (can define an over sampling ratio, OSR= N_s / N_t), solution obtained with Least-Squares approach

- For $N_s = N_t$ and $N_s > N_t$ Computational cost (number of model evaluations) can be very high for large number of uncertain variables

- If $N_s < N_t$, the system is underdetermined (sparse sampling approach) but the most efficient in terms the computational cost

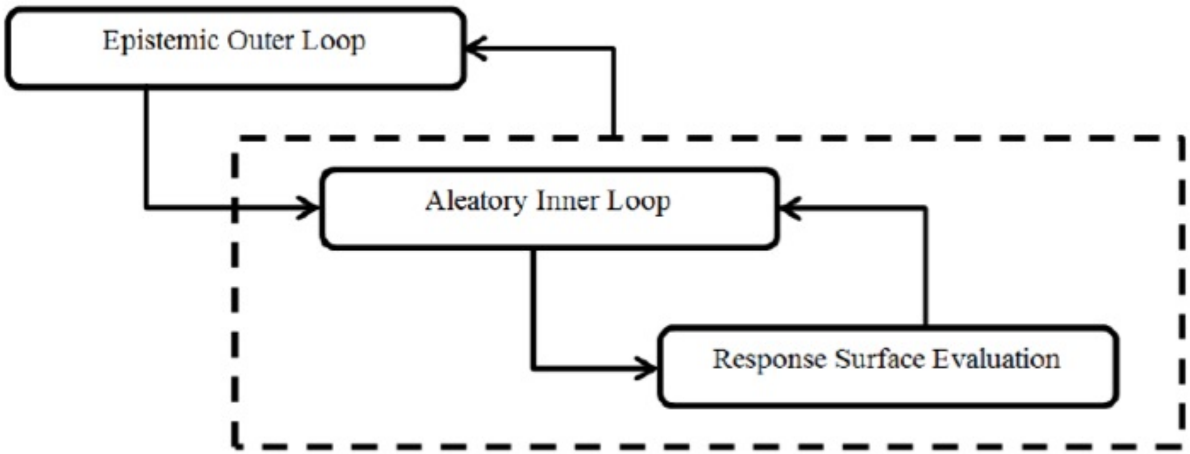
  - Seek a solution to the sparse system with the fewest number of **non-zero** coefficients in the response surface using optimization:

$$\min \|\alpha\|_1 \quad \text{subject to} \quad \left\|\Psi\alpha - \alpha^*\right\|_2 \leq \delta$$

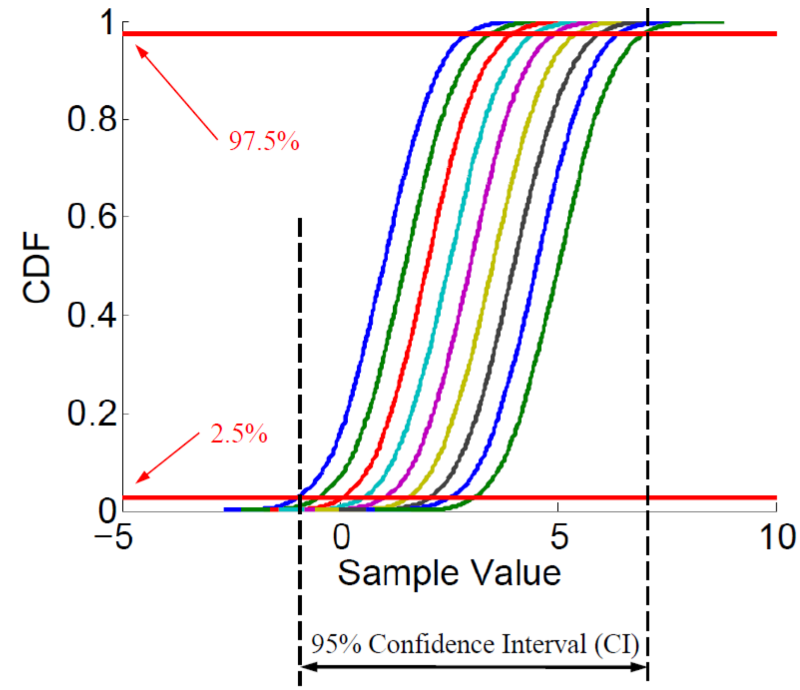
  - Incrementally update N_s until convergence achieved. Check convergence at iteration i with an error defined on Sobol indices:

$$\mu_{e,i} = \frac{1}{n}\sum_{j=1}^{n} S_{e_{i,j}} \quad \text{where} \quad S_{e_{i,j}} = \|S_{T,i,j} - S_{T,i-1,j}\|$$

Mixed Uncertainty Propagation



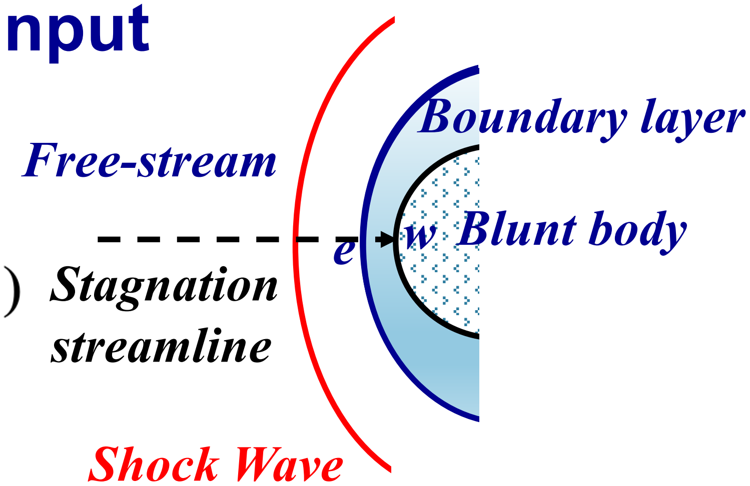
Total # of samples = (epistemic samples) x (aleatory samples)
(each sample corresponds to a CFD simulation)



- Double-loop sampling to generate a set of cumulative density functions (CDFs)
- Generates a probability or “P-box” representation of the mixed uncertainty output
- The bounds of a probability level or statistics (e.g., standard deviation) can be obtained by optimization or sampling over the epistemic variables
- A stochastic response surface used in place of the deterministic code for computational efficiency

Stagnation Point Heat Flux Prediction in Hypersonic Flow with Uncertain Input

Fay-Riddell Correlation (laminar boundary layer in thermo-chemical equilibrium, fully catalytic wall) :



$$\dot{q}_w = 0.76(Pr^{-0.6})(\rho_w \mu_w)^{0.1}(\rho_e \mu_e)^{0.4}\sqrt{\frac{\mathrm{d}u_e}{\mathrm{d}x}}(h_{0_e} - h_w) \times \left(1 + (Le^{0.52} - 1)\frac{h_D}{h_{0_e}}\right)$$

Velocity gradient :

$$\frac{\mathrm{d}u_e}{\mathrm{d}x} = \frac{1}{R_n}\sqrt{\frac{2(P_e - P_\infty)}{\rho_e}}$$

Dissociation enthalpy :

$$h_D = \sum_i c_i (h_f^0)_i$$

Radiative-adiabatic wall BC:

$$\dot{q}_r = \dot{q}_d + \dot{q}_c = \dot{q}_w$$

$$\dot{q}_r = \epsilon \sigma T_w^4$$

Epistemic Uncertain Variables

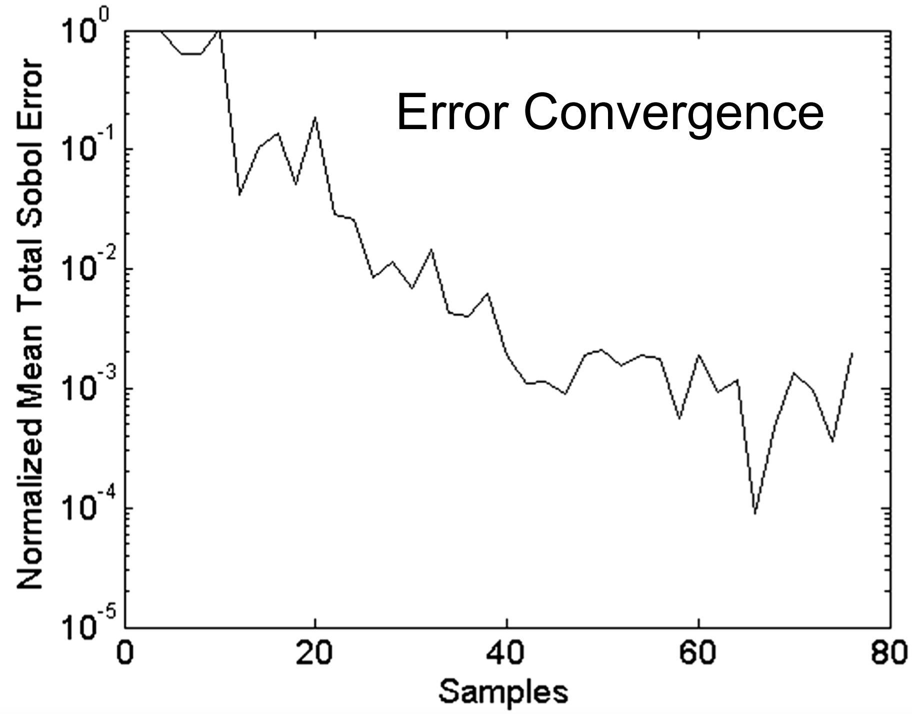
Variable	Minimum	Maximum
Le	1.358	1.442
Pr	0.679	0.721
μ_e factor	0.97	1.03
ϵ	0.776	0.824
h_f^0 (N) factor	0.97	1.03
h_f^0 (O) factor	0.97	1.03
Power on Le	0.5044	0.5356

Aleatory Uncertain Variables

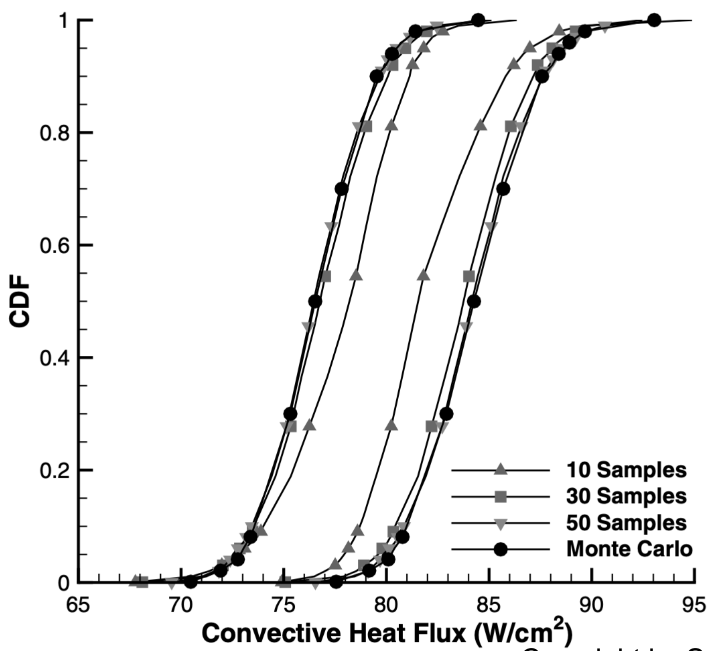
Input	Distribution	Mean	CoV, %
U_∞, m/s	Gaussian	7.3152e + 03	1
ρ_∞, kg/m^3	Gaussian	5.30e − 05	1
T_∞, K	Gaussian	2.1201e + 02	1
R_n, m	Gaussian	3.048e − 01	1

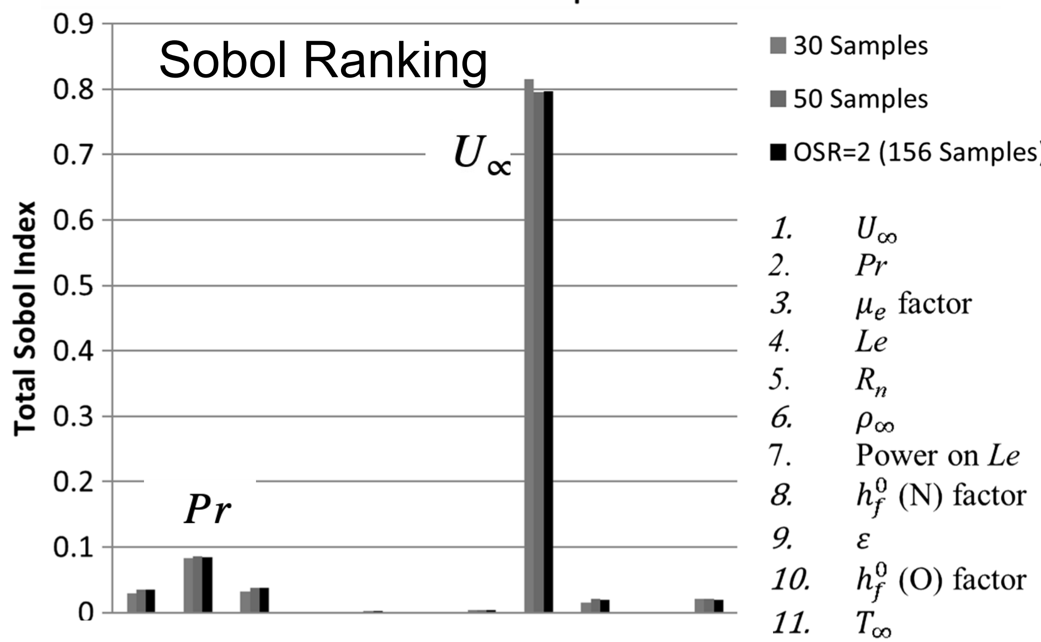
Sparse-Sampling NIPC Results

- 11 uncertain variables, 2nd degree polynomial, N_t =78
- When N_s= 50, Sparse-Sampling NIPC results identical with Monte-Carlo (400,000 Samples) and NIPC with OSR=2 (156 samples)



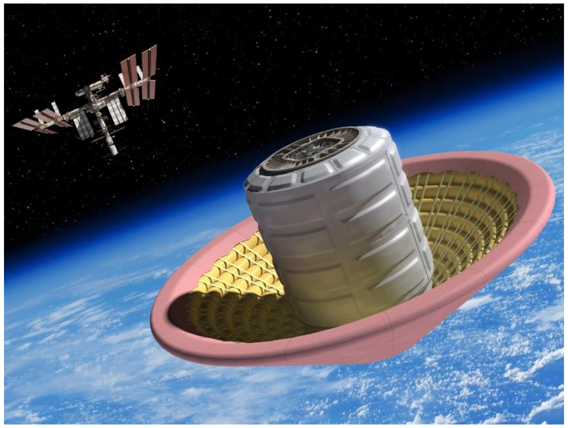
P-Box Comparison

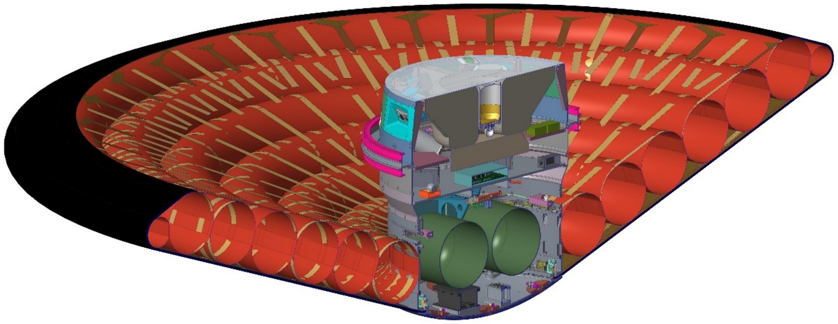




Hypersonic Inflatable Aerodynamic Decelerator (HIAD)

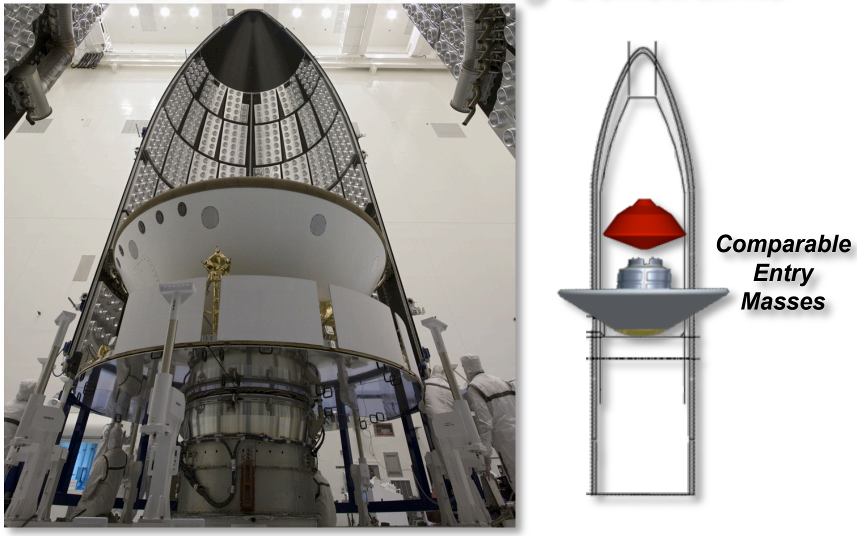
- HIAD concept primarily being developed to address increased capability needed for landing higher mass at higher altitudes on Mars, eventually for human missions



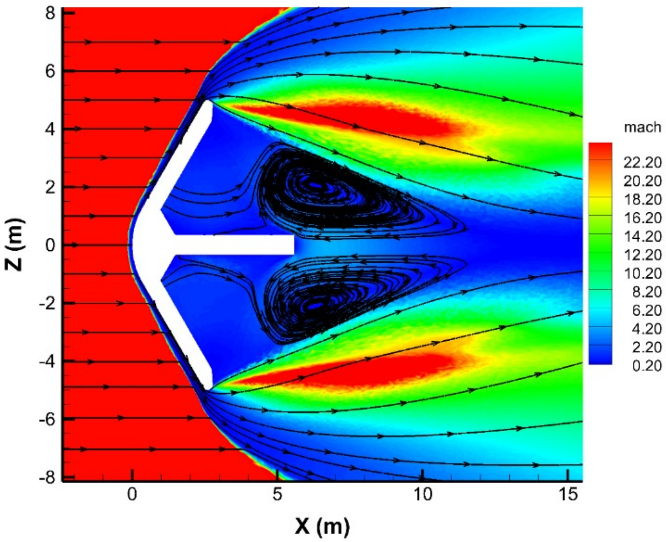


- Uses inflatable concentric toroids to deploy flexible-thermal protection system (f-TPS)

Launch Vehicle Fairing Constraints

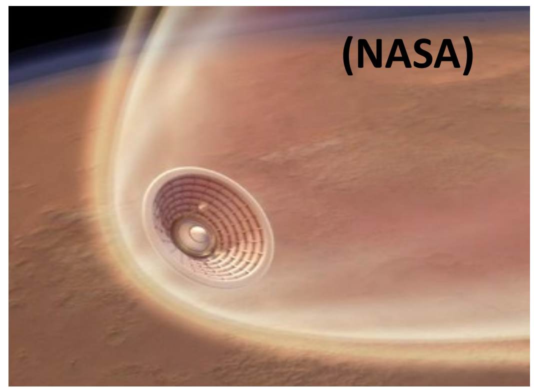


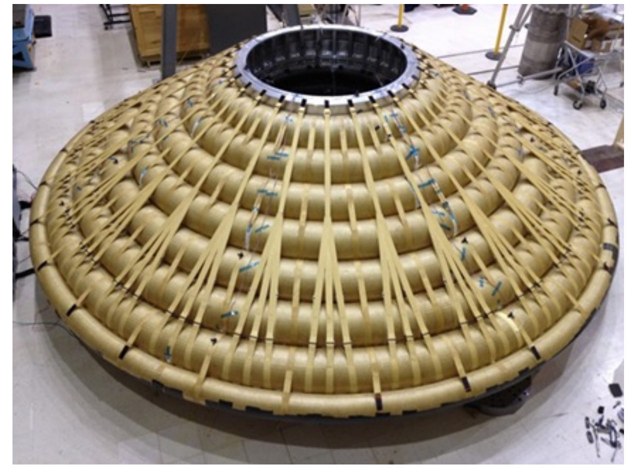
UQ for Multidisciplinary HIAD Analysis & Design



Hypersonic flow modeling [7]

Fluid-structure interaction (FSI)

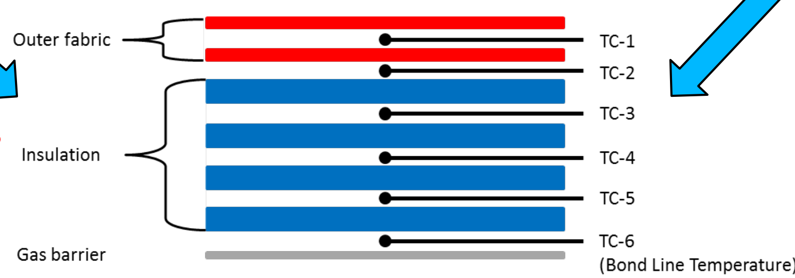




Structural modeling [8]

Material Thermal Response

Material Thermal Response



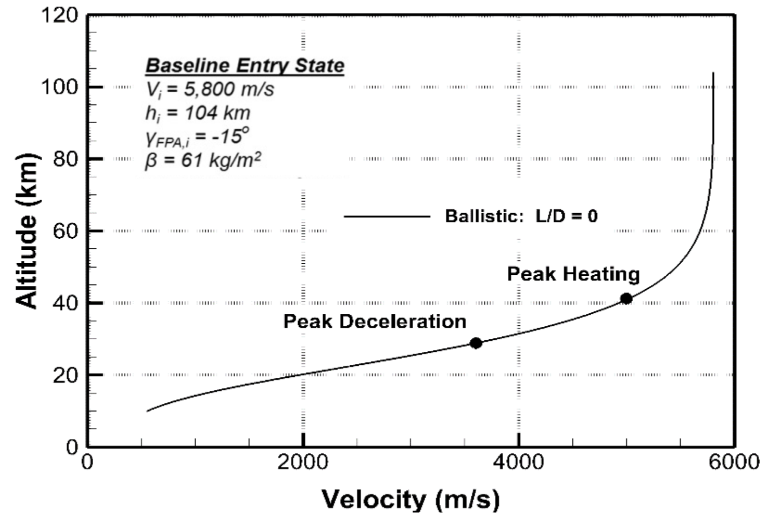
Flexible TPS Modeling [9]

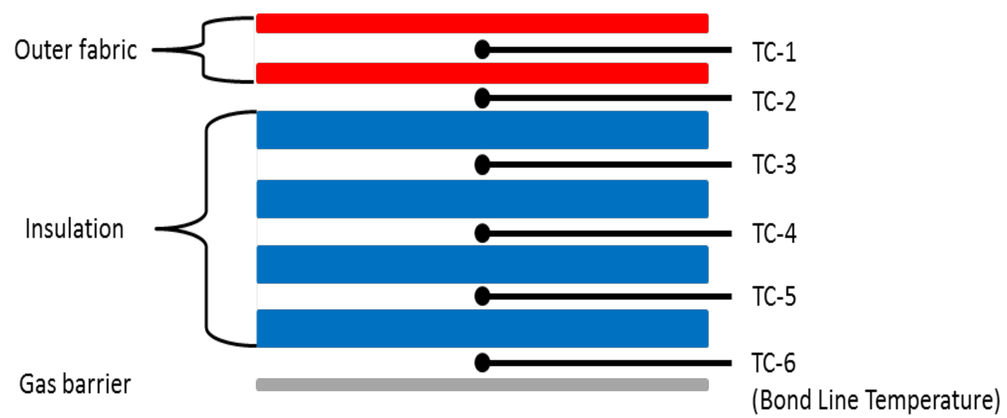
HIAD Modeling Uncertainties:

- Operating (freestream) Conditions
- Physics-based modeling parameters
  - Thermochemistry
  - Inflatable Structure Response
  - F-TPS Response

Objectives of the HIAD UQ Analysis

- Consider a 10m diameter HIAD for Ballistic Mars Entry
- Identify significant flow field and FSI uncertainty sources on surface quantities (aerodynamic heating, shear and pressure) for sensitivity and uncertainty analysis of F-TPS response
- Perform sensitivity and uncertainty analysis for F-TPS response
  - Quantify the uncertainty in the bondline temperature of F-TPS layout

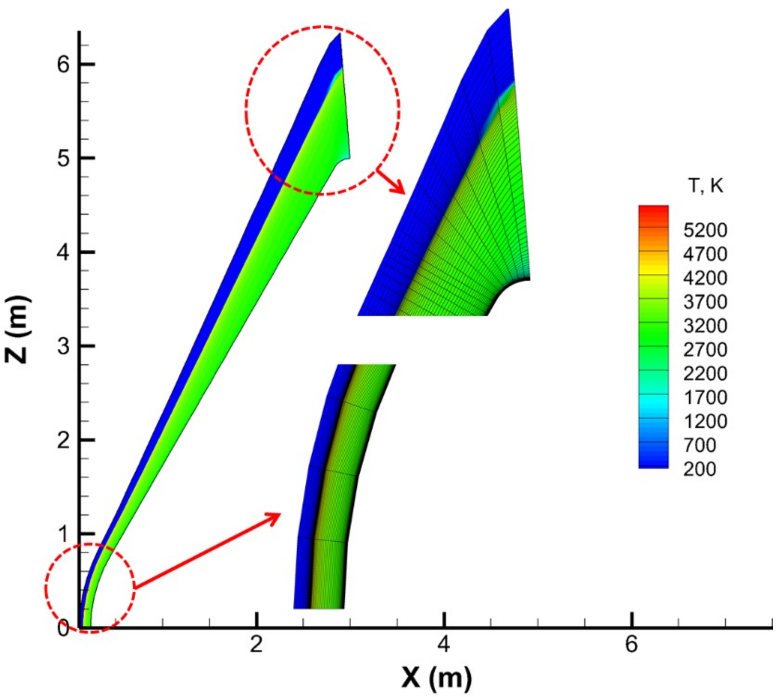




Computational Model for F-TPS Analysis

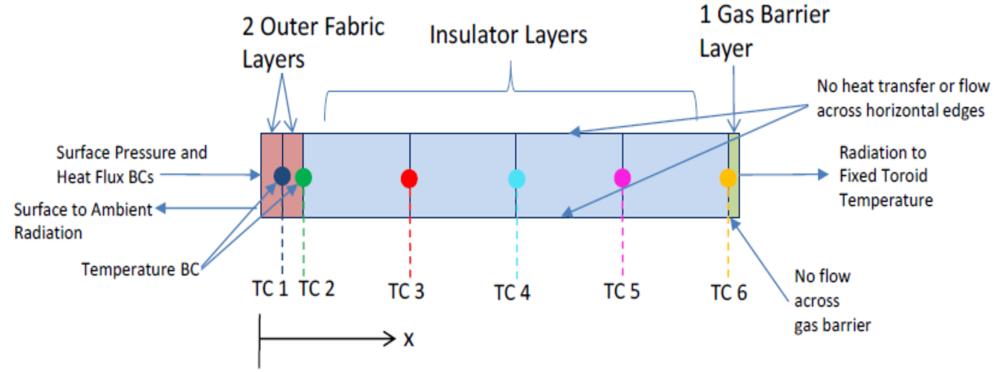
Shock-Layer RANS Solution (CFD)

- NASA LAURA solver
- Two-temperature thermochemical non-equilibrium model by Park with 8-species Mars composition
- 1-D grid adaptation to resolve shock and boundary layer gradients
- Super-catalytic wall and fully turbulent boundary layer assumed for "most conservative" heating conditions



Thermal Response Model

- 1-D solid conduction, radiation, gas conduction, and advection heat transfer modeled through porous media
- Decomposition of the insulation material at elevated temperatures
- Thermal properties of each material layer and gas determined from experimental measurements



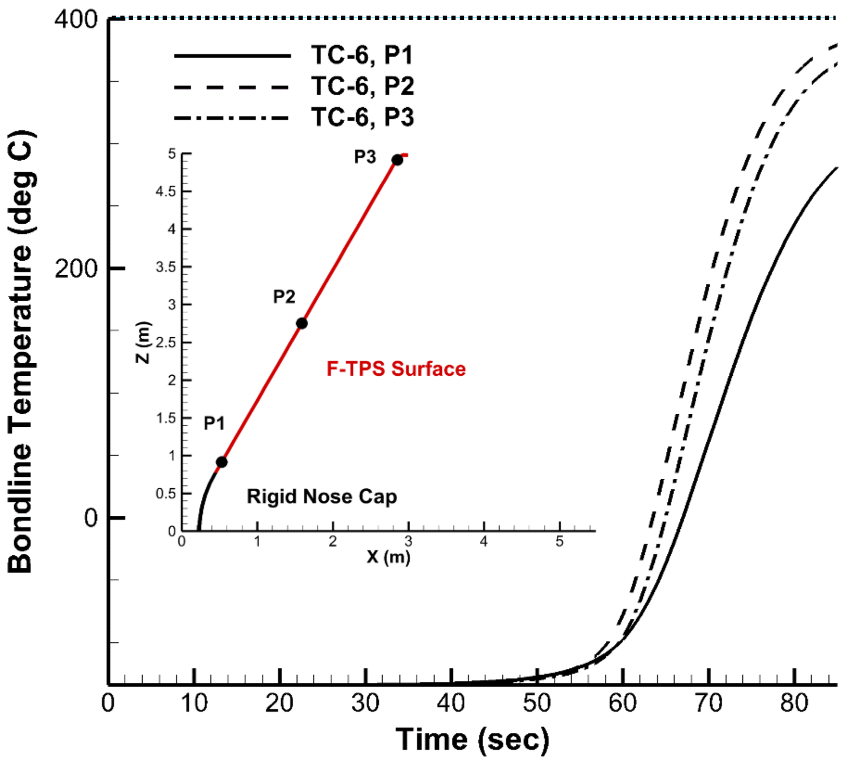
$$\rho_s C_{ps} \frac{\partial T}{\partial t} - \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + \rho_g C_{pg} v_{gx} \frac{\partial T}{\partial x} + H_d \frac{\partial \rho_s}{\partial t} = 0$$

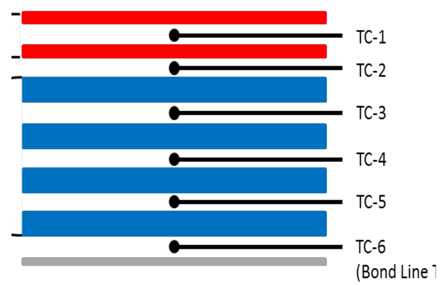
$$\phi \frac{\partial \rho_g}{\partial t} - \frac{\partial}{\partial x}\left(\rho_g v_{gx}\right) = -\frac{\partial \rho_s}{\partial t}$$

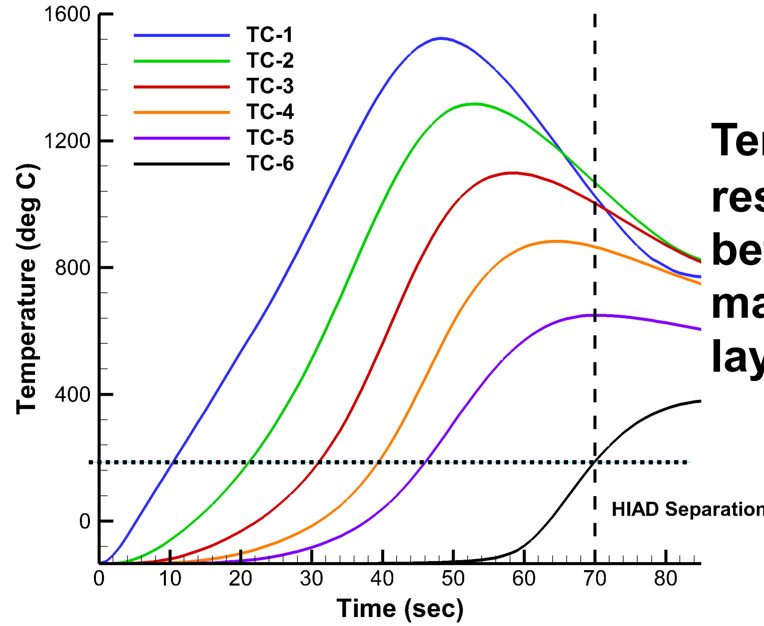
$$v_{gx} = -\frac{k_x}{\mu_g} \frac{\partial p}{\partial x}$$

F-TPS Thermal Model

Baseline Results with No Uncertainty







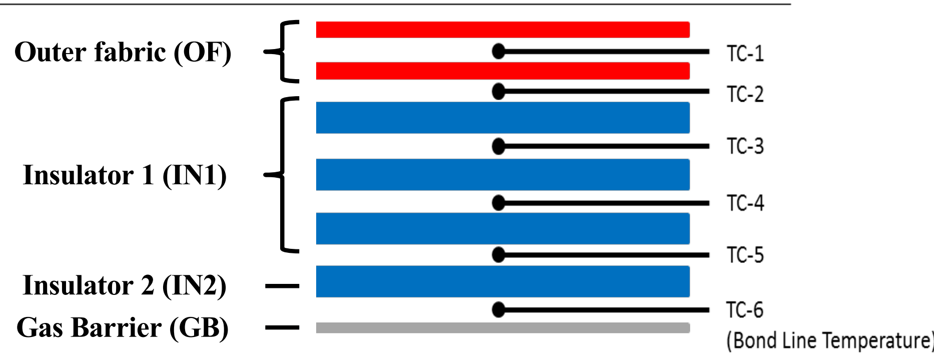
Temperature response between material layups at P2

- Critical bondline temperature at 3 locations

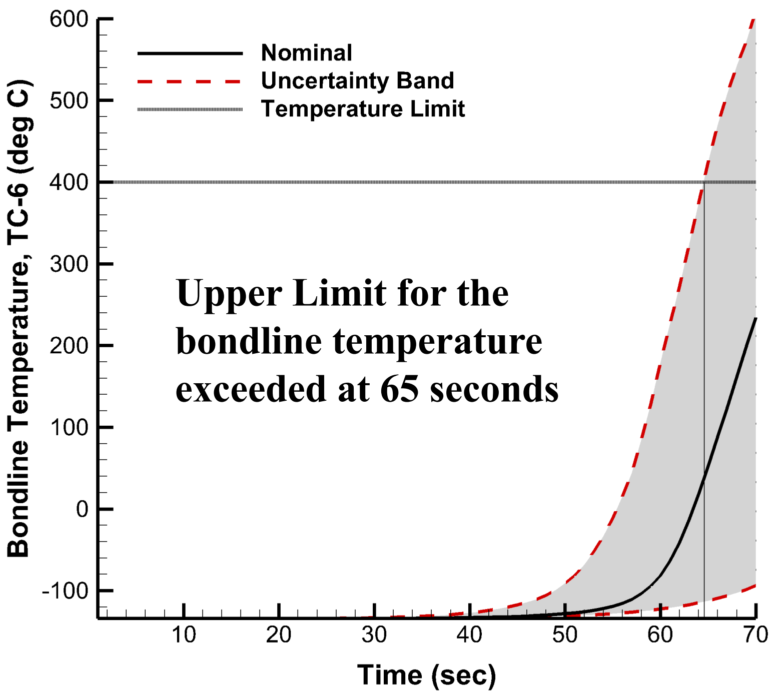
Uncertainty Sources for F-TPS Response Analysis

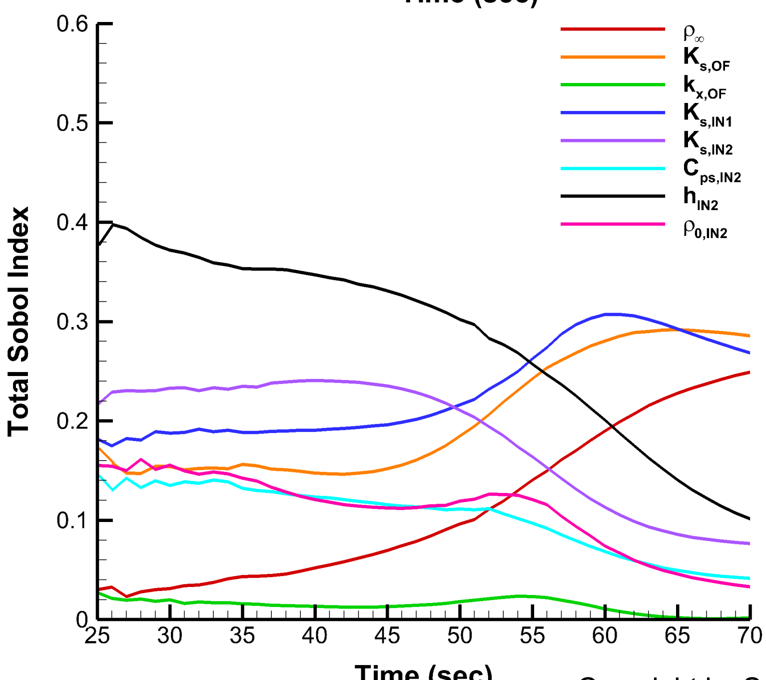
Uncertain Component	Uncertain Parameter	Description	Classification	Uncertainty	Ref.
Aerodynamic heating (convective), surface pressure	ρ_∞	Freestream Density	Aleatory (Uniform)	±30%	
	V_∞	Freestream Velocity	Aleatory (Normal)	0.5% CoV	AIAA 2015-3581[24]
	$A_{CO2\text{-}CO2}$	CO_2-CO_2 Binary Collision	Epistemic	±30%	JSR Vol. 52, No. 3[16]
	$A_{CO2\text{-}O}$	CO_2-O Binary Collision	Epistemic	±30%	
Nicalon SiC outer fabric (2)	$K_{s,OF}$	OF Thermal Conductivity	Epistemic	±30%	
	$k_{x,OF}$	OF Permeability	Epistemic	±30%	Same as IN1
	ϵ	OF Emissivity	Epistemic	±10%	uncertainties
	$C_{ps,OF}$	OF Specific Heat	Epistemic	±20%	
KFA5 insulator layers (3)	$K_{s,IN1}$	IN1 Thermal Conductivity	Epistemic	±30%	Expert Opinion
	$k_{x,IN1}$	IN1 Permeability	Epistemic	±30%	Expert Opinion
	$C_{ps,IN1}$	IN1 Specific Heat	Epistemic	±20%	Expert Opinion
	$h_{1,IN1}$	IN1 Layer 1 Thickness	Aleatory (Normal)	3% CoV	Expert Opinion
	$h_{2,IN1}$	IN1 Layer 2 Thickness	Aleatory (Normal)	3% CoV	Expert Opinion
	$h_{3,IN1}$	IN1 Layer 3 Thickness	Aleatory (Normal)	3% CoV	Expert Opinion
Pyrogel 2250 insulator layer	$K_{s,IN2}$	IN2 Thermal Conductivity	Epistemic	±30%	Expert Opinion
	$k_{x,IN2}$	IN2 Permeability	Epistemic	±30%	Expert Opinion
	$C_{ps,IN2}$	IN2 Specific Heat	Epistemic	±20%	Expert Opinion
	h_{IN2}	IN2 Layer Thickness	Aleatory (Normal)	10% CoV	Expert Opinion
	$\rho_{0,IN2}$	IN2 Virgin Density	Aleatory (Normal)	10% CoV	Expert Opinion
	$E_{a,IN2}$	IN2 Activation Energy	Epistemic	±20%	AIAA 2016-1513[34]
Kapton LN backing material	$K_{s,GB}$	GB Thermal Conductivity	Epistemic	±15%	Expert Opinion
	$C_{ps,GB}$	GB Specific Heat	Epistemic	±5%	Expert Opinion
TOTAL	22				

- Significant aero-heating uncertainty sources determined from the sensitivity analysis of hypersonic flow field (out of 59 variables)
- F-TPS thermal model uncertain variables introduced for the material thermal properties, layer thicknesses, and decomposition phenomena



F-TPS Bondline Temperature Uncertainty and Sensitivity





- Greatest uncertainty occurs just prior to HIAD separation at 70 seconds – transition to secondary descent technology
  - 125% above and 75% below the nominal bondline temperature values
- Increase in bondline temperature uncertainty beyond 40 sec due to thermal gradients in outer fabric and insulator 1 layers; freestream density at lower altitudes near peak deceleration

Uncertain Component	Uncertain Parameter	Description
Aerodynamic heating (convective), surface pressure	ρ_∞ 3	Freestream Density
	V_∞	Freestream Velocity
	$A_{CO2-CO2}$	CO_2-CO_2 Binary Collision
	A_{CO2-O}	CO_2-O Binary Collision
Nicalon SiC outer fabric (2)	$K_{s,OF}$ 1	OF Thermal Conductivity
	$k_{x,OF}$	OF Permeability
	ϵ	OF Emissivity
	$C_{ps,OF}$	OF Specific Heat
KFA5 insulator layers (3)	$K_{s,IN1}$ 2	IN1 Thermal Conductivity
	$k_{x,IN1}$	IN1 Permeability
	$C_{ps,IN1}$	IN1 Specific Heat
	$h_{1,IN1}$	IN1 Layer 1 Thickness
	$h_{2,IN1}$	IN1 Layer 2 Thickness
	$h_{3,IN1}$	IN1 Layer 3 Thickness
Pyrogel 2250 insulator layer	$K_{s,IN2}$	IN2 Thermal Conductivity
	$k_{x,IN2}$	IN2 Permeability
	$C_{ps,IN2}$	IN2 Specific Heat
	h_{IN2}	IN2 Layer Thickness
	$\rho_{0,IN2}$	IN2 Virgin Density
	$E_{a,IN2}$	IN2 Activation Energy
Kapton LN backing material	$K_{s,GB}$	GB Thermal Conductivity
	$C_{ps,GB}$	GB Specific Heat

Conclusions

- Outlined a framework for flight uncertainty prediction of hypersonic entry vehicles
- Described efficient aerothermal uncertainty quantification with stochastic expansions
- Demonstrated the uncertainty quantification approach on thermal protection system response of an HIAD for Mars entry
- Integrating uncertainty quantification to entry vehicle development (e.g., HIAD) early in the design process also important for timely changes in vehicle configuration, TPS selection/sizing, increasing robustness, and resource allocation for ground and flight testing

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