Entry Systems and Technologies Division

Uncertainty Quantification and Statistical Engineering for Hypersonic Entry Applications

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RTO-AVT-VKI short course on Uncertainty Quantification

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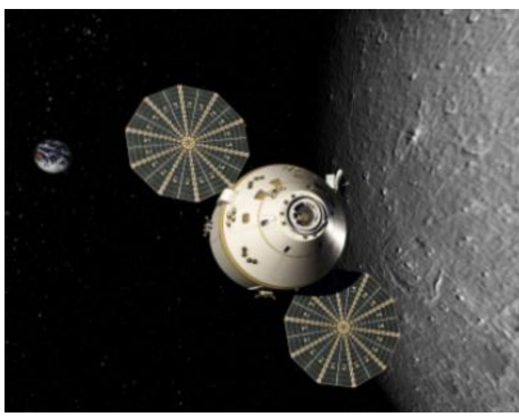

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Uncertainty Quantification

Uncertainty quantification (UQ) is the science of quantitative characterization and reduction of uncertainties in applications.

It tries to determine how likely certain outcomes are if some aspects of the system are not exactly known.

EXAMPLE 1:
predict the acceleration of a human body in a head-on crash with another car

even if we exactly knew the speed, small differences in the manufacturing of individual cars, how tightly every bolt has been tightened, etc, will lead to different results that can only be predicted in a statistical sense.

EXAMPLE 2:
predict the performance of the Thermal Protection System (TPS) during atmospheric entry

even if we exactly knew the trajectory, small differences in the atmosphere, the manufacturing of the material and how it was processed, etc, will lead to different results that can only be predicted in a statistical sense.

Statistical Engineering

Statistical Engineering is a difficult task targeting the quantification of the order underlying randomness

Deterministic Engineering ...

... answers a question with a single number, assumed to occur with certitude, while probabilistic methods provide a range of likely answers, plus a statement on the probability of a given result.

Statistical Engineering ...

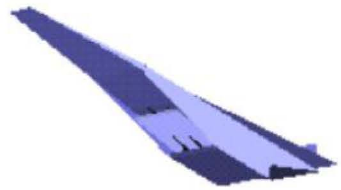
... makes predictions about uncertain future events based on less than ideal observations of the past.

It quantifies factors often left to intuition, like uncertainty, incomplete information and complicated interdependencies ...

... and thus leverages the engineer's understanding of how things work with the statistician's capacity to figure out why when they don't.

Hypersonic Entry

$$\text{ratio} = \frac{\text{Object Speed}}{\text{Speed of Sound}} = \text{Mach Number}$$



Hypersonic
Mach>5.0

Supersonic
Mach > 1.0

Transonic
Mach = 1.0

Subsonic
Mach < 1.0

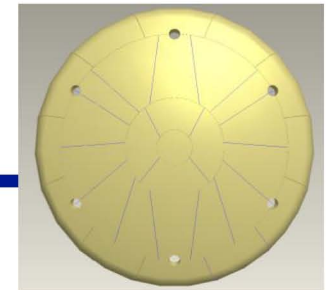
Regime	Mach	mph	km/h	m/s
Subsonic	<0.8	<768	<1,230	<340
Transonic	0.8-1.2	610-768	980-1,470	270-410
Supersonic	1.2-5.0	768-3,840	1,470-6,150	340-1,710
Hypersonic	5.0-10.0	3,840-7,680	6,150-12,300	1,710-3,415
High-hypersonic	10.0-25.0	7,680-16,250	12,300-30,740	3,415-8,465
Re-entry speeds	>25.0	>16,250	>30,740	>8,465

Hypersonics from a chemistry perspective:
-Plain hypersonic: internal energy relaxation
-High-hypersonic: gas dissociation
-Re-entry speeds: ionization and radiation

Outline

- Introduction to Heat shield design
- Motivation for Statistics based HS design
  - Application of TPS Standardized Policy
  - Mission Risk and Reliability Requirements
- UQ for TPS Thermal Sizing Margin Management Process
  - Margins, Rationale and Sensitivity Trades
  - Thermal Margin
- UQ and Statistical Engineering for Flight Data Reconstruction
  - Stardust
  - MEDLI
- Conclusions

Why a heatshield?



•To protect the vehicle/astronauts from the high heat generated during slowing down (friction) upon atmospheric reentry

•To reject heat by re-radiation and/or pyrolysis and ablation

Other methods of slowing down:

•lower Ballistic coefficient (same mass for a larger dimension vehicle) <------> lower heating

•Entry Inflatable Aerodynamic Decelerator (low level of development)

•Propulsive descent (retro rockets) = prohibitive payload mass and fuel

The Shuttle:

•Earth orbit velocity (altitude dependent) ~28,000 km/h (17,500 MPH)

•Fires its engines against direction of travel — reduces speed by ~325 km/h (200 MPH) - leads to orbit shape change while spending all the fuel on board (!!)

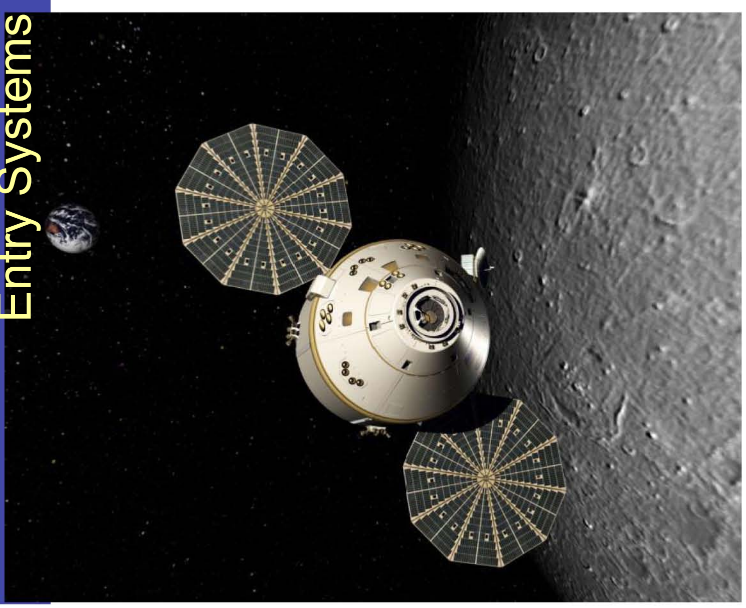
Why not use the Shuttle to go to the Moon?

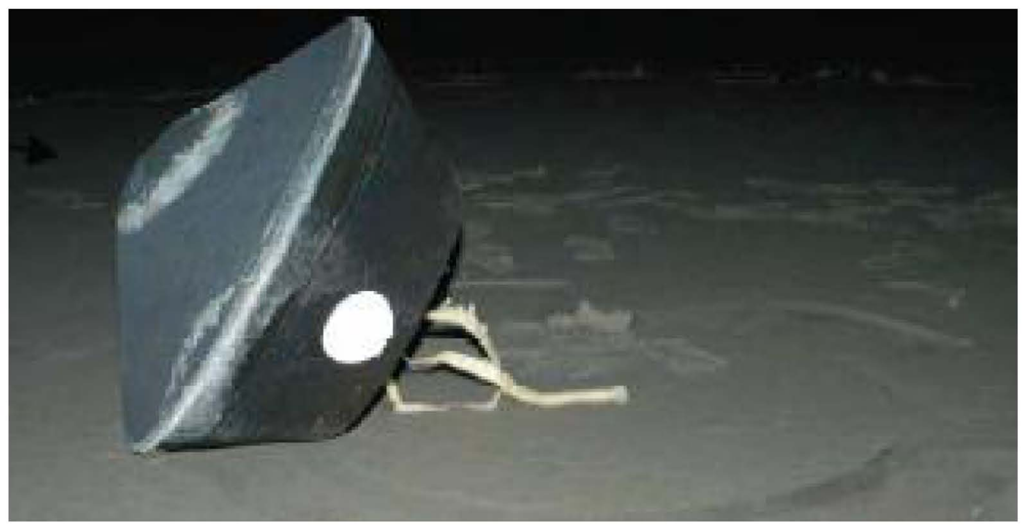
- Not designed for such purpose -winged vehicle
- Moon return velocity is ~40,000 km/h (25,000MPH)
- Slowing down requires unthinkable type of fuel and amount…
- …adding additional mass also needed to be carried to the Moon, requiring more fuel, and bigger engines…

Purpose of Heatshield design

Thermal Protection System (TPS) DESIGN:

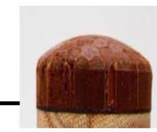
1. TPS material selection
2. TPS thickness
3. TPS mass
4. TPS distribution on the exterior of a vehicle
5. minimizing the overall mass





Conditions experienced during reentry

The only NASA probe to fly an ablative heatshield with seams/gaps/joints was the 1.25 meter diameter Galileo. In the past **decade**, NASA has not flown anything larger than 2.65 meters in diameter.

Mission	TPS	Max Total Heat Flux (W/cm^2)	% Radiative	Heat Load (kJ/cm^2)	Diameter (m)	Manufacture	Image
Apollo (1967-1973)	Avcoat	850	25%	30	3.9	Monolithic	
Shuttle (1981-2009)	Reusable	70	1%	70	0.15x0.15 x0.07	Tiles	
Stardust (2006)	PICA	950	15%	28	0.8	Monolithic	
MSL (2009)	PICA	300	0%	6	4.5	Segmented	
Orion Lunar Return (2018)	PICA or Avcoat	650	50%	100	5.0	Segmented (PICA) or Monolithic (Avcoat)	
LE-X (2013)	PICA or Avcoat	1170	60%	44	2.0	Segmented (PICA) or Monolithic (Avcoat)	

Motivation for Statistics based Heat Shield Design

- **Orion and MSL have demonstrated the need to develop a standardized framework that links the TPS design process to a mission reliability/ safety requirement based on two criteria:**
  - Assessment of TPS underdesign at the expense of the mission success
  - Assessment of TPS overdesign at the expense of additional mass
- **This framework needs to be tailored to each class of TPS materials and quantified through testing and analysis**
- **Existing mathematical linkage between margins and reliability is complemented and validated by experts opinions**
- **Developing custom policies is costly to flight projects resulting in the use of non-optimum heritage based designs.**
- **Application to Commercial Cargo/Crew:**
  - NASA must define criteria for accepting commercially developed TPS designs based on human safety/reliability standards.
  - A rigorous TPS reliability margin, safety and design procedure enables independent assessment and more reliable commercial vehicles.

Applications

- **Applicable to all human and robotic atmospheric entry systems**
  - Applicable missions: LEO, Access to and Return from ISS, planetary exploration, and sample return

- **Primarily used in the design and validation phases of vehicle development**
  - Used in the operational phase for reliability assessment

- **Key components include:**
  - a standardized policy for TPS margins management
  - statistical analysis derived margins
  - a mathematical linkage between margins and reliability
  - entry level data sets for low, mid and high density ablators
  - test methods, test infrastructure, and technical expertise
  - Flight instrumentation, ground test program definition

- **Results in lower costs, high confidence optimized designs, and schedule reductions. It also enables a wider spectrum of missions with low cost and high reliability.**

Flight Data Reconstruction

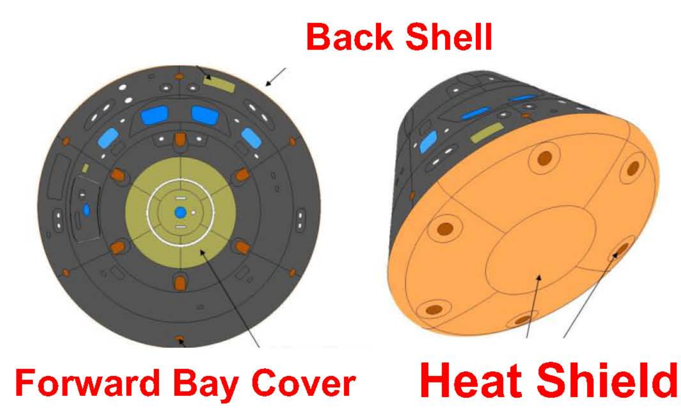
Flight data is the gold standard for final model validation

- To reduce overall design uncertainties
- To validate the aerothermal and TPS design tools
- To improve understanding of the extrapolation of Earth-based ground testing to the flight environment

System Loss of Crew/Mission Requirements

- Mission System Engineering defines vehicle risk requirements (SRD) for various scenarios (ISS return, Lunar return, etc)
- SRD defines the Loss of Mission Total (LOM_T) and Loss of Crew (LOC) and the risk allocations to capture
  - average/nominal mission risks
  - abort risks
- The <u>TPS Subsystem </u>LOM of 1 loss in 5000 missions (1/5000) is sub-allocated:

Heat Shield	50%	50%	10,000	10,000
Back Shell	40%	40%	12,500	12,500
Forward Bay Cover	10%	10%	50,000	50,000
TPS Subsystem	**100%**	**100%**	**5,000**	**5,000**



Example for ORION (~2009):
Heatshield LOC Allocation:50%
Equivalent Risk Allocation: 5000*50/100=10,000
The Risk and allocation numbers are fictitious!

Heatshield Subcomponents

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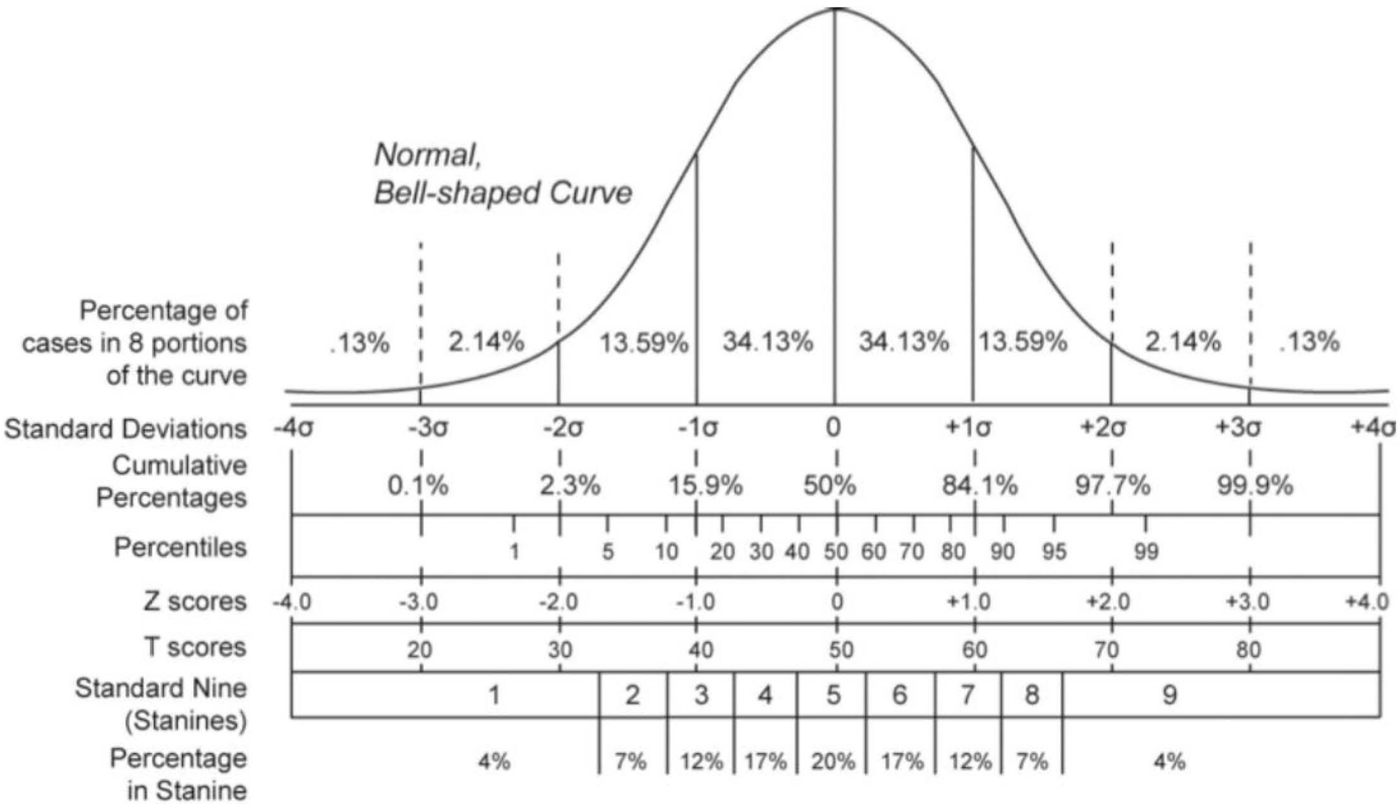
Heat Shield	50%	50%	10,000	10,000
Back Shell	40%	40%	12,500	12,500
Forward Bay Cover	10%	10%	50,000	50,000
TPS Subsystem	**100%**	**100%**	**5,000**	**5,000**

- **Overall heatshield reliability allocations include:**
  - **Thermal Performance**
  - Mechanical/Structural
  - Damage Tolerance
  - Design Singularities/Closeouts

- **Thermal Performance is historically one of the largest contributors to heatshield mass, while simultaneously one of the least rigorously defined of the design margins**

Heatshield Thermal Performance:
Risk and Reliability



- use the tail of the distribution (statistics outside of N-sigma) to derive a risk of failure. This actually gives us a measure of the probability that the actual average is outside the predicted range.
- The standard deviation (amount of spread) of the number of failures is roughly equal to the square root of the average number of failures.
- For example: for HS allowable risk is 1/10000 meaning one failure in 10000 = 0.0001=0.01%
- Reliability is ~99.99% equivalent to 3σ-4σ

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TPS Sizing: What does it mean?

- **TPS sizing starts with a nominal prediction**
  - Using the best analysis tools available, what is the required thickness to meet bondline temperature requirement assuming zero dispersions or uncertainties?
  - Are there also structural considerations? (Coupled thermo-structural modeling)
  - Effects of singularities in the TPS system
- **Margin is then added to the nominal thickness to account for dispersions and uncertainties in the material, its response, and the environment it is subjected to**
  - Application of margin has been done at varying levels of fidelity, ranging from engineering judgment to probabilistic analysis
  - A good understanding of the underlying physics, and the inherent uncertainties or deficiencies in the models of that physics, is required to rigorously evaluate margin

A rigorous process was instituted by NASA starting with MSL and CEV/Orion, but it is still being developed and enhanced. A key impediment has been the availability of experimental data to validate the stated model uncertainties

Overview

1. **TPS Thermal Sizing Margin Management Process**

2. **Overview of current heatshield design process**
   - **Required input (vehicle level)**
   - **Thickness determination/optimization (Heatshield interface)**

3. **Origin of uncertainties**

4. **Margins**

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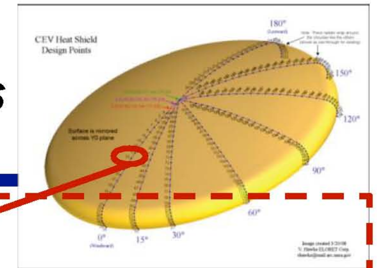
TPS THERMAL Sizing Margin Management Process



Nominal Trajectory

Aerodynamics, Atmosphere, Navigation and Guidance Parameters

GN&C

CAP

Nominal Material Response
to hit bond-line temperature

Trajectory Dispersion

Aero-thermal Margin

Not To Exceed Bondline Temperature

BTMM=-108⁰F

BTMM=Bondline Temperature Material Margin

CASE 0: Nominal Thickness & Recession
T_0, R_0

CASE 1: Dispersed Thickness & Recession,
T_1, R_1

CASE 2: Aerothermal Thickness & Recession,
T_2, R_2

CASE 3: Material Thickness & Recession,
T_3, R_3

FINAL MARGINED THICKNESS:

MAX OF

Baseline+Recession Thickness, T_b $+\Delta T_R$

OR

Margined Thickness, FOS*T_b

FOS = Factor of Safety (1.05-1.1)

RSS Process

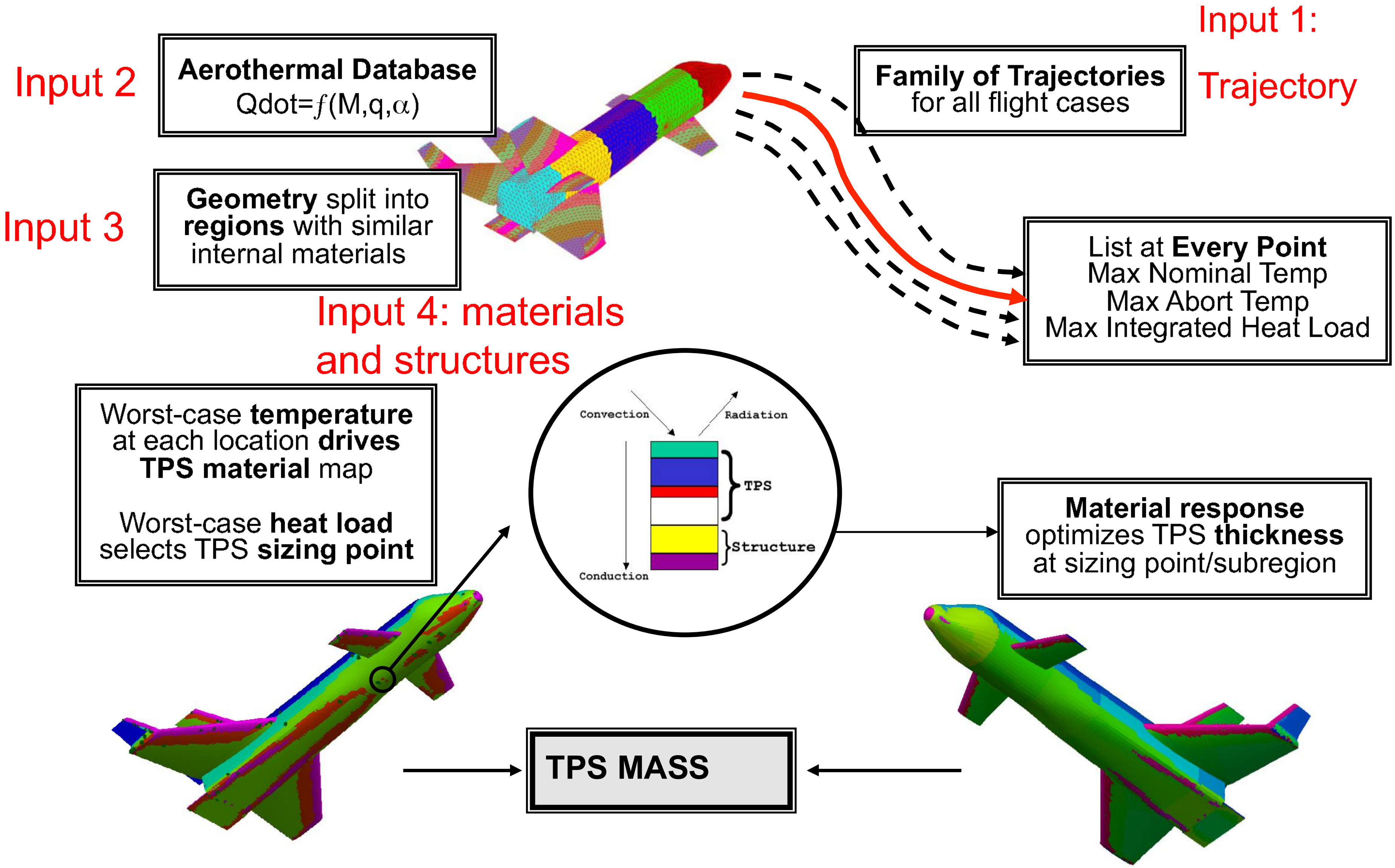
$$T_b = T_1 + \sqrt{\left[(T_2 - T_1)^2 + (T_3 - T_1)^2\right]}$$

$$\Delta T_R = (K - 1)(T_{R-1} + \sqrt{\left[(T_{R-2} - T_{R-1})^2 + (T_{R-3} - T_{R-1})^2\right]}$$

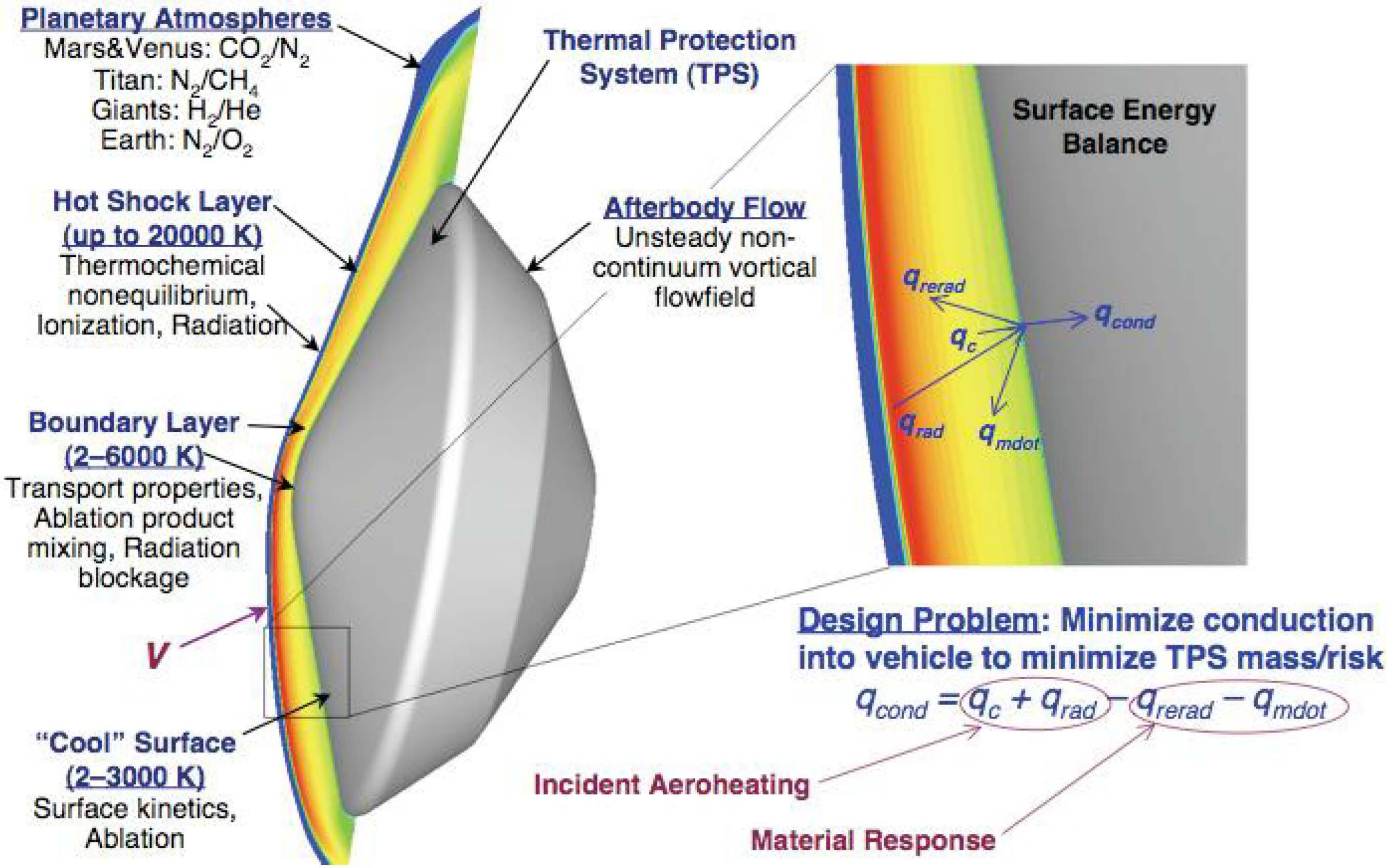
Recession Margin	k=
PICA	1.2
Carbon Phenolic	1.2
Avcoat	1.25

 NOMINAL MARGINS Reliability Requirement

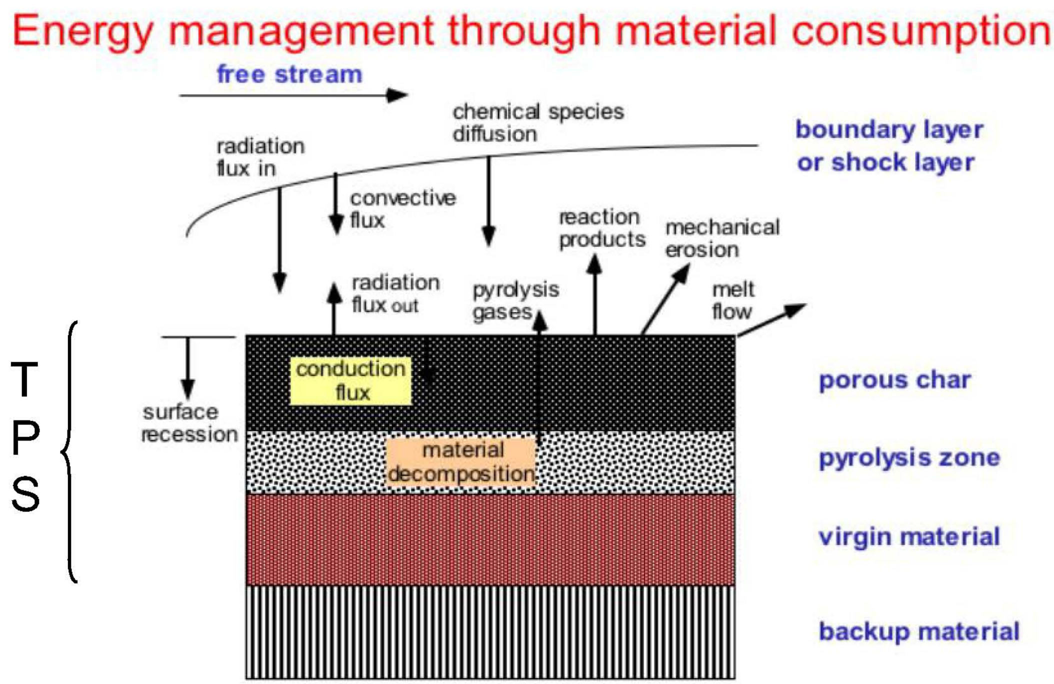
Overview of current heatshield design process



Physics of Aerothermal environments



Physics of Material response



- 1D time-accurate solution of thermal diffusion with surface ablation and internal pyrolysis
- PYROLYSIS: an internal, endothermic thermal decomposition of the solid releasing gaseous species without consumption of gas species from the boundary layer gas
- ABLATION: sum of processes that remove mass from the surface (vaporization, sublimation, reaction of solid or liquid to produce gaseous species, melt flow, spall of solid)

Physics and chemistry based models:

1. For the solid:

    -phase change reactions (virgin solid -> charred solid+Pyrolysis gas)

    -for these three constituents: macroscale properties from measurements, known chemistry, theory and thermodynamics from NIST/JANNAF data

2. At the surface:

    -complex surface energy balance

    -thermochemical ablation model

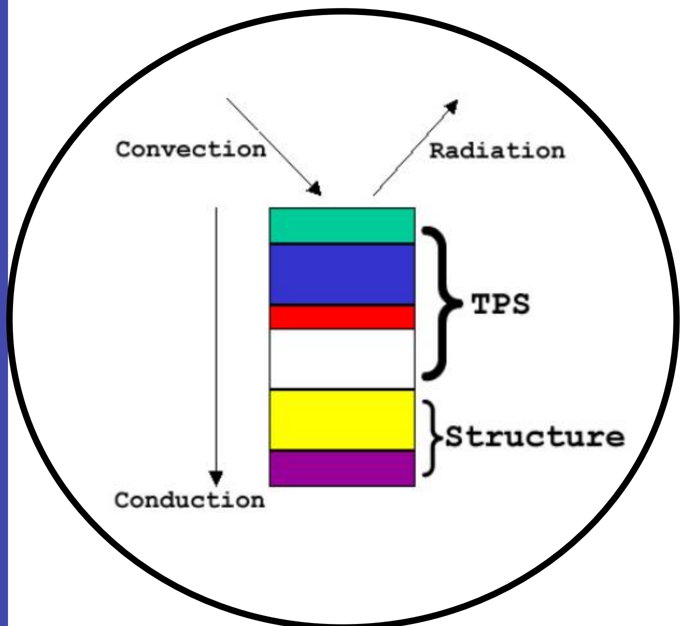
    -boundary layer heat transfer with blowing correction

Defining the TPS Thickness via optimization

- **Optimization criteria:**
  Not To Exceed (NTE) Bondline Temperature Limit (BLT)

•Usually defined at the interface between ablative material and bonding agent

•Could use more than one optimization constraint



Steps during optimization:

•At each time step in the program the calculated BLT is checked against the NTE imposed limit

•Material is added if BLT> NTE or removed if BLT<NTE

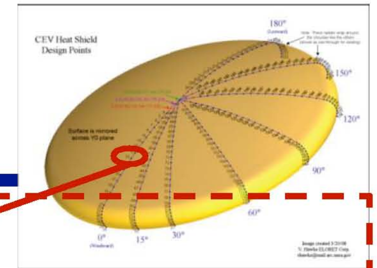
•Final thickness value is optimized for BLT=NTE

Material response program outputs for each point on the heatshield:

•the optimized thickness

•Recession

TAILORABLE TPS THERMAL Sizing Margin Management Process



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CASE 3: Material Thickness & Recession, T_3, R_3

Reliability Requirement

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MAX OF

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OR

Margined Thickness, $FOS*T_b$

FOS = Factor of Safety (1.05-1.1)

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Key Uncertainties in the TPS Design Process

- **TRAJECTORY DISPERSION (3sigma)**

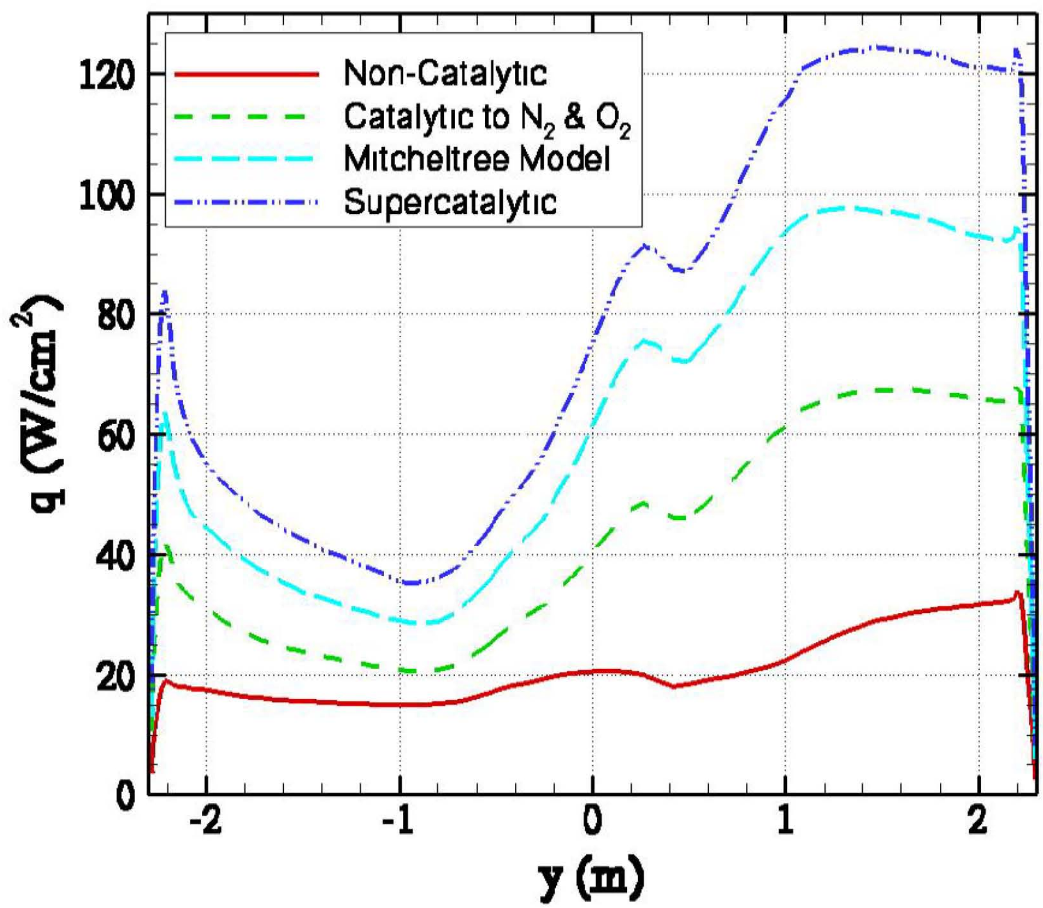
- **AEROTHERMAL ENVIRONMENTS:**
  - ✓Wind Tunnel to CFD comparison
  - ✓Shuttle data: orbiter reports 2-sigma error in winward heat flux
  - ✓CFD discrepancies from physical models:
    - ✓Turbulence
    - ✓<u>Chemistry model</u>
    - ✓<u>Convective heating</u>
    - ✓<u>Blowing Reduction in Ch</u>

Gas-Surface Interactions

- In lieu of a good validated GSI model for PICA in dissociated CO_2, the MSL aerothermal team assumed supercatalytic wall for desig

- Result is (likely) over-prediction of required thickness, total recession, and margin assigned to these effects

- Fortunately in this case we expect flight data from the MEDLI experiment on MSL t help validate improved GSI models



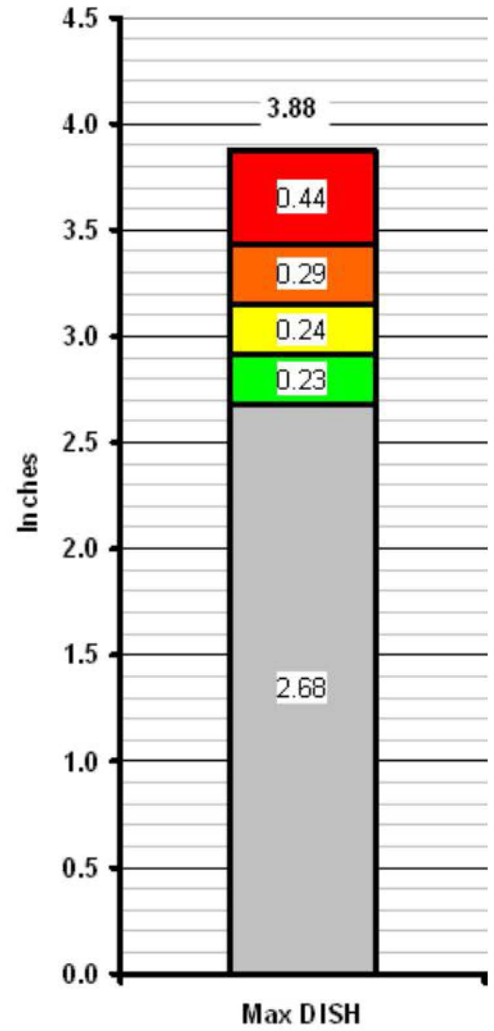
MATERIAL RELATED UNCERTAINTIES

- **Recession Margin = Discrepancies between measurements and arc jet data**
  - Requires arc jet test database over the entire range of expected operation of the material
  - Requires consideration of non-thermal recession (spallation, melt, etc.)
  - Specific to ablative materials

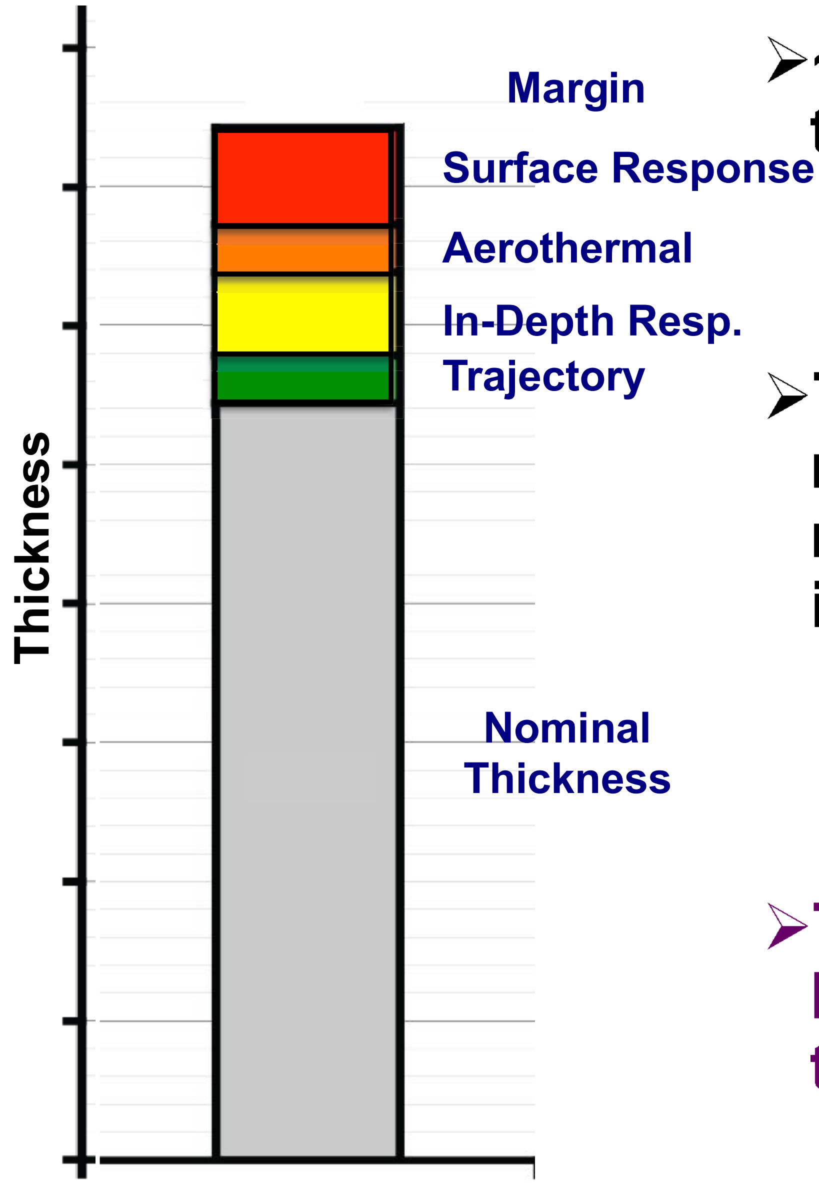
- **Factor of Safety = Ground to Flight Traceability**
  - Defined so far by "expert's call"
  - Derived from comparison of model prediction to Flight Data (Stardust, MSL/MEDLI, others!!)
  - Requires development of Inverse Parameter Estimation methods

- **Bondline Temperature Material Margin = Material Property Variability**
  - Fundamentally statistical by nature
  - Requires rigorous input uncertainties, derived through dedicated material testing
  - Requires correct Monte Carlo procedure

- **Sensitivity Trades = Prioritize investment based on TPS mass impact**



Results: sample case



- ~75% of the total thickness is the nominal (zero-margin) value
  - All margins considered contribute about 25% to the thickness
- The two largest contributions to margin are those primarily from material response (surface and in-depth)
  - Trajectory and aerothermal effects are less important since ablators are excellent accommodators of heat
- **The secret truth: there is a lot of hidden margin in the nominal thickness!!!**

Why is there MARGIN in the NOMINAL?

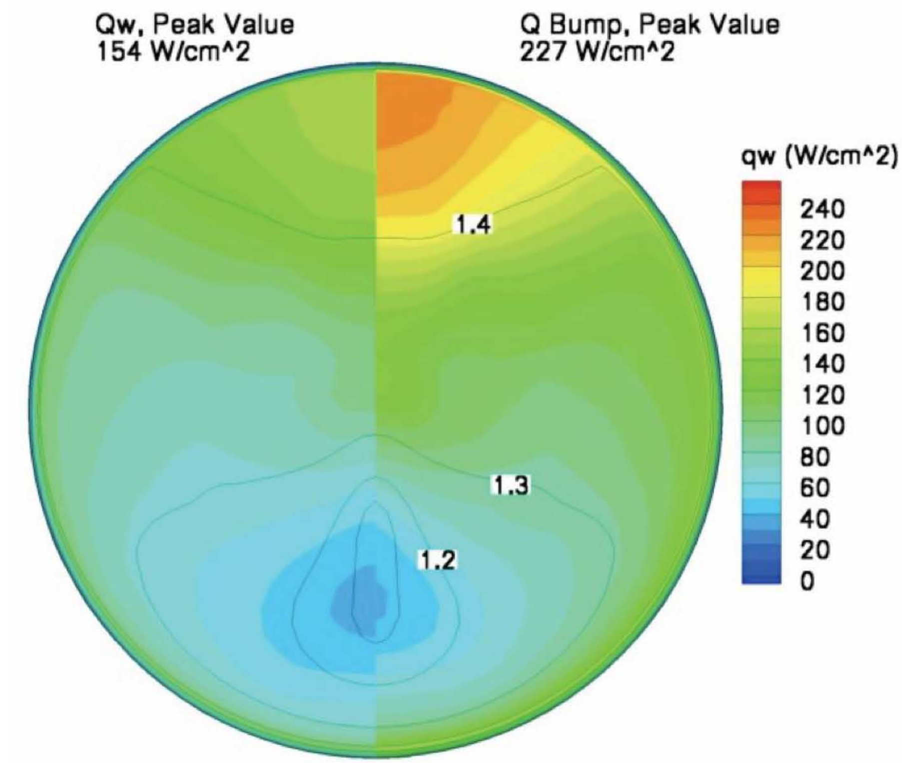
- **Engineers are, well, engineers. We build the best models we can with the data available, but tend to err on the side of conservatism when we do not have sufficient data**

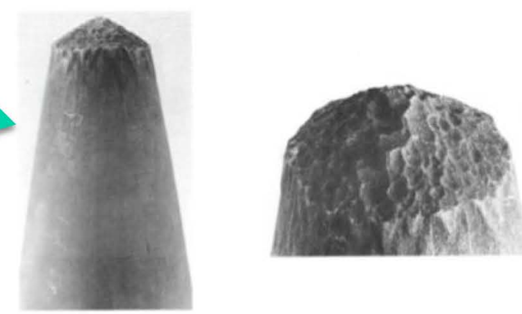
- **The more empirical the model, the more conservative it tends to be**
  - This conservatism is fairly ad-hoc; it is usually not known <u>how</u> conservative the model is

- **Examples to follow…**

Roughness Effects

- Roughness augmentation to heating and recession remains poorly understood
- Ground test data cannot reproduce necessary flight physics (BL thickness, turbulence intensity, etc.)
- As a consequence, we design with primarily empirical models, making (we hope) conservative estimates of worst case impact on heating and recession
- We know that in some cases scalloping and cross hatching can become large, but we cannot predict onset at this time

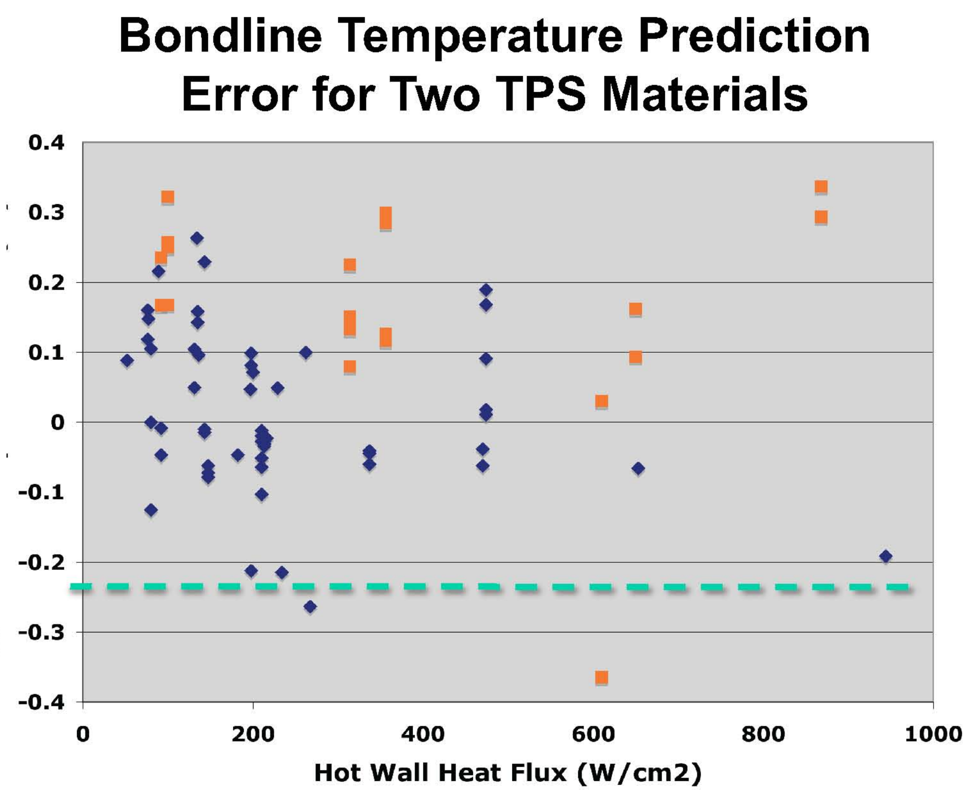




Roughness represents ~30% contribution to surface heating; could be outside of MEDLI resolution

MATERIAL RESPONSE BIASES

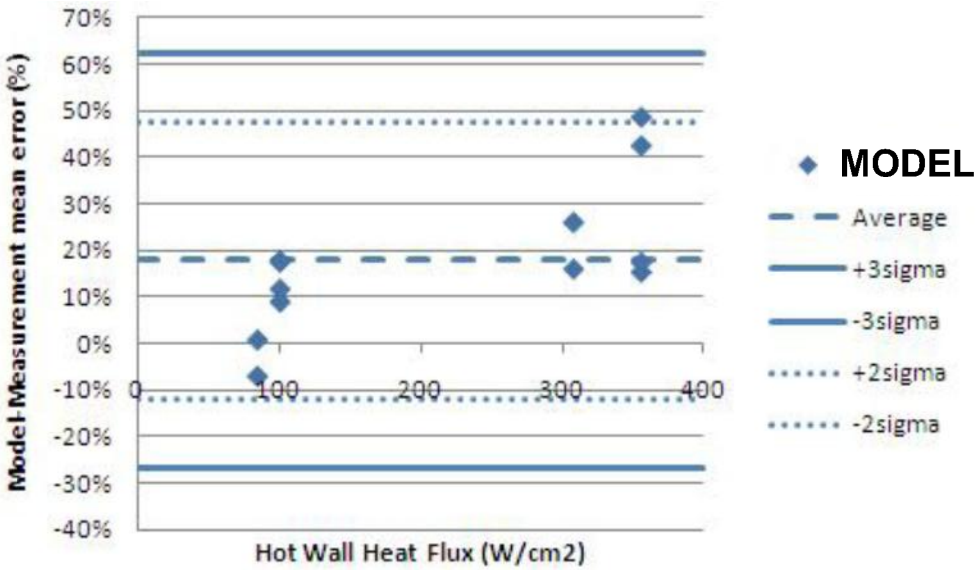
- TPM performance dispersions due to things like material variability are part of margin; accounted for (ideally) with repeat tests, material property testing over multiple batches
- Dispersions are expected, but a good physics model should have little or no BIAS
- However, because engineers are engineers, this is frequently not the case
- In this example, bondline temperature is over-predicted for both the “orange” and “blue” materials, leading to “margin” in the nominal

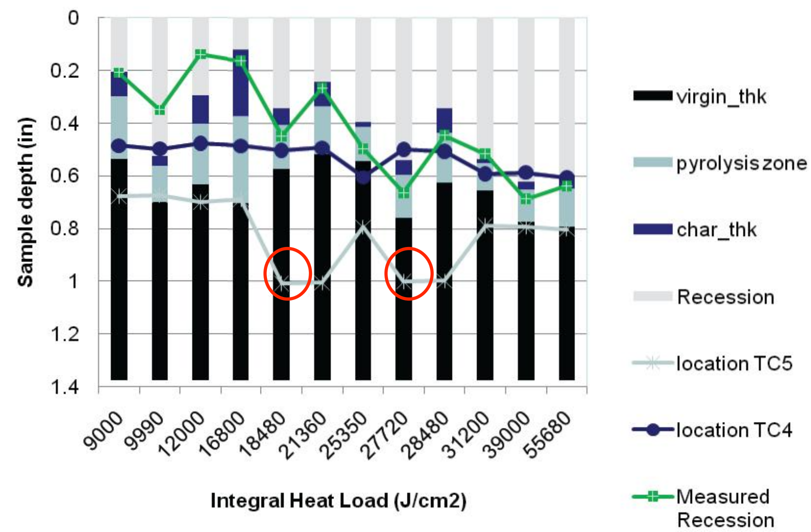


BIAS:
BLUE MATERIAL~8%
ORANGE MATERIAL ~14%

MATERIAL RESPONSE DISPERSIONS

ArcJet test for validation of Material Response Model for Bondline Thermal Performance





Analysis:
12 samples
Mean error = 18%; σ = ±15%
Inferred Bondline Temperature Material Margin = 228°F

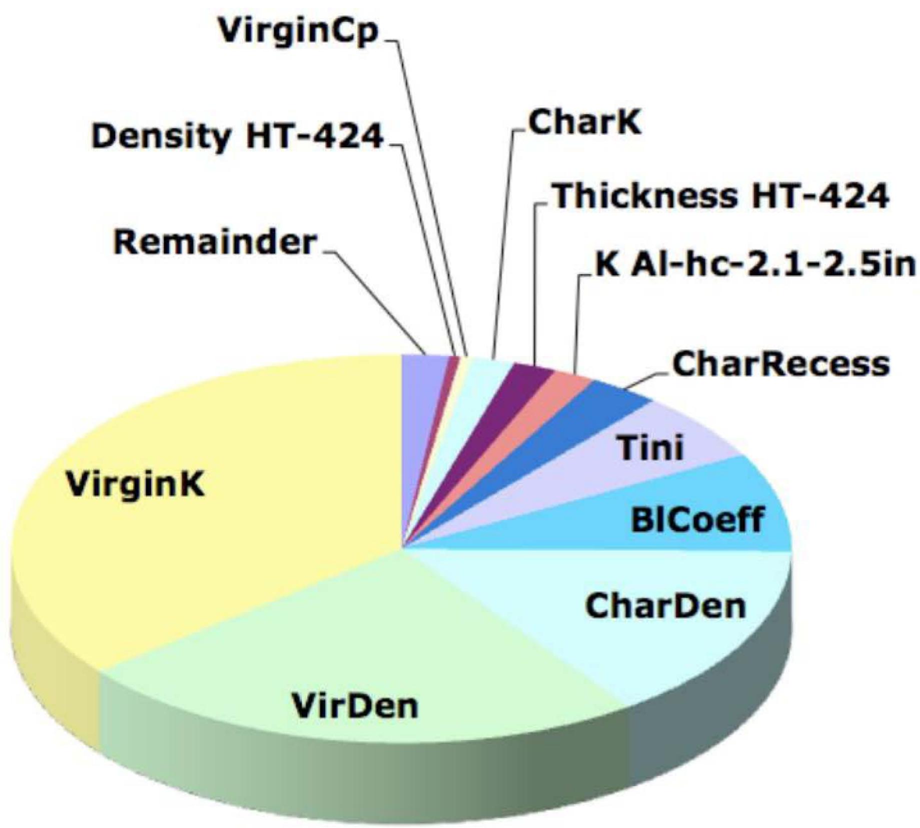
Exclude samples with error>40%
Mean error = 12%; σ = ±9%
Inferred Thermal Margin = 146°F

BONDLINE TEMPERATURE MATERIAL MARGIN

- **Design of ground test programs in support of margins development and risk assessment**
- **Smart use of instrumentation during ground testing (ArcJet)**
- **Ground testing of flight instrumentation**

Material Response Unaccounted Phenomena (False Negatives)

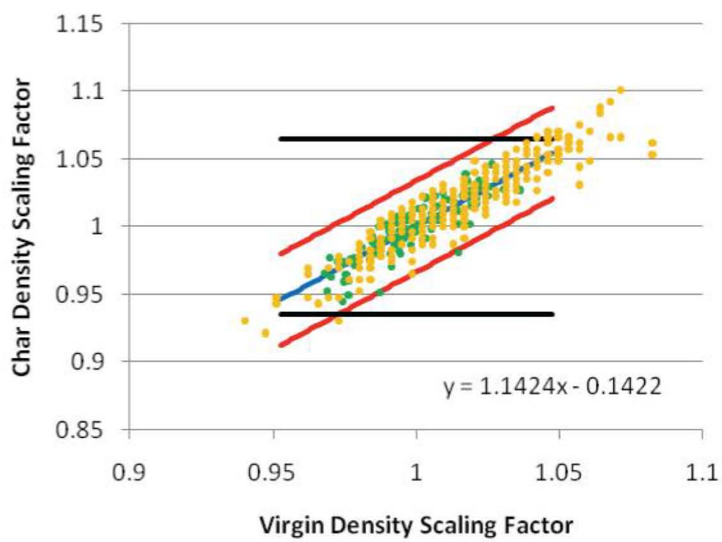
- We are becoming increasingly reliant on probabilistic error analysis
- However, the results of the analysis are only as good as the physical model being evaluated (GI>GO)
- Probabilistic methods cannot expose fundamental flaws in the models employed, and may lead to false confidence if one is not careful
- Example at right: what is missing?



  - Common sense says that pyrolysis gas enthalpy should matter; it is the primary in-depth energy accommodation mechanism. Yet it doesn't appear. Why not? Are current models deficient?

Material Properties Testing Supporting Uncertainty Quantification

- Goal:
  - Monte Carlo based margin derivation
  - Determine which parameters contribute the most to the measurements uncertainty
  - Associate the parameters to be estimated with appropriate ranges of measurements
  - Input 2σ uncertainties for material properties and heating parameters
  - Account for correlations between variables according to experimental data



Material Variable	2σ Uncertainty
Virgin Density	5%
Char Density	Corr.
Virgin Specific Heat	5%
Char Specific Heat	10%
Virgin Conductivity	15%
Char Conductivity	15%
Virgin Emissivity	3%
Char Emissivity	5%
Resin Decomposition Rate	20%
Pyrolysis Gas Enthalpy	20%
Char Recession, B'_c	4%
Initial Material Temperature	5%

Aerothermal Variable	2σ Uncertainty
Surface Pressure	15%
Blowing Coefficient	20%
Heat Transfer Coefficient	15%

Bondline Temperature Material Margin
Proposed approach

AJ Data

Ablation Model

Flight

Model error: σ_{data}

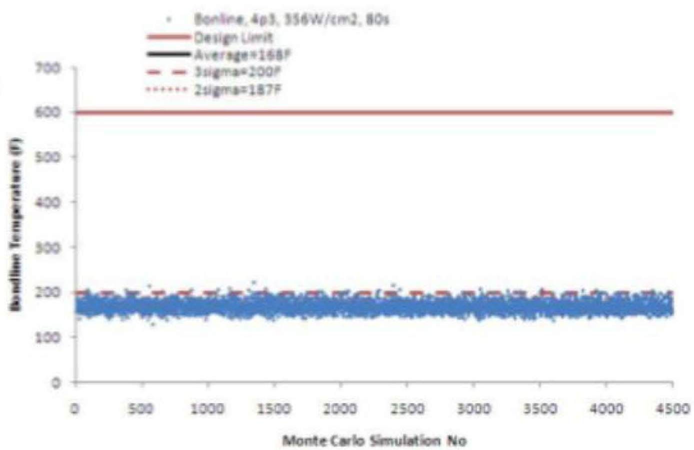
Monte Carlo on Arc Jet data: $\sigma_{groundBL}$

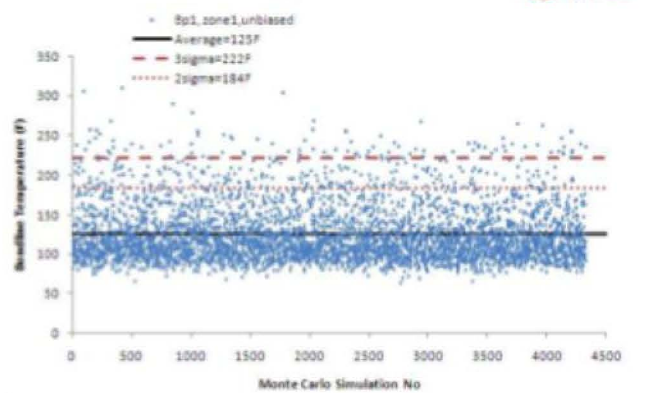
$$TM = (T_{design} - T_{init}) * \sigma_{data} * \frac{\sigma_{flightBL}}{\sigma_{groundBL}}$$

$$if \quad \sigma_{data} = \sigma_{groundBL} \quad then:$$

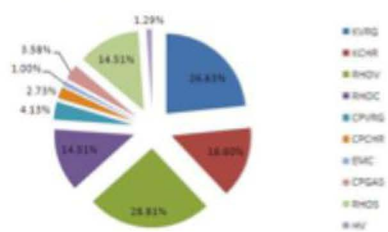
$$TM = (T_{design} - T_{init}) * \sigma_{flightBL}$$

Monte Carlo on flight data: $\sigma_{flightBL}$

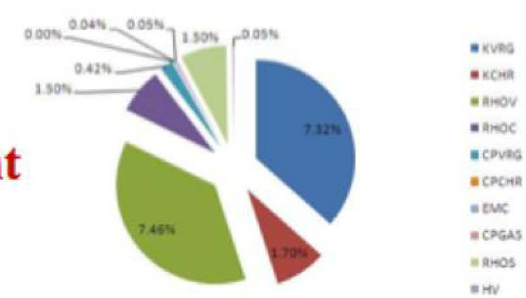




Arc Jet

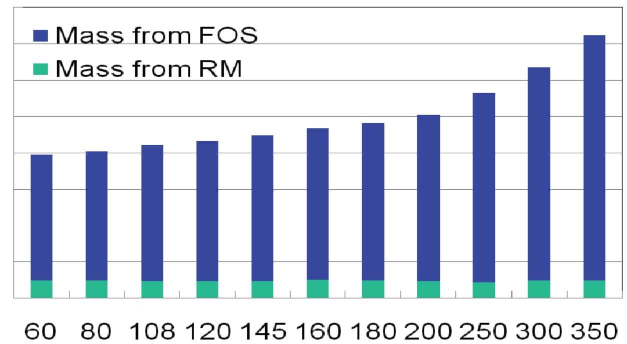


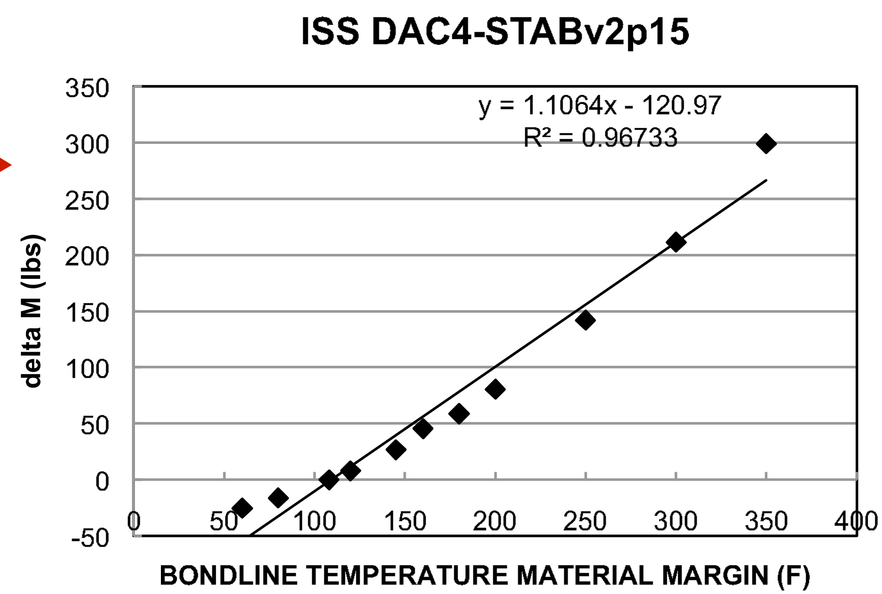
Flight



HS Mass: Sensitivity Trades

Analysis Assumption ISS/Lunar		DAC4 Avcoat
General Assumptions		
Aerothermal Database (Turbulent)		V0.73
Initial Temperature		70°F
Structure NTE temperature		500 °F
Radiation Sink Temperature		70 °F
Aerothermal Uncertainties		
Aerothermal Margins	Pressure	1.05
	Shear	1.00
	Convection	1.10 to 1.35 [a]
	Radiation	1.56
Atmospheric/Trajectory		
Dispersion Margins		[b]
TPS Margins and FoS		
Bondline Temperature Material Margin		108 °F
Recession Uncertainty		1.25
Default FoS		1.1
Fail Lien, Recession Bias		0 %
Margin Application		
		RSS

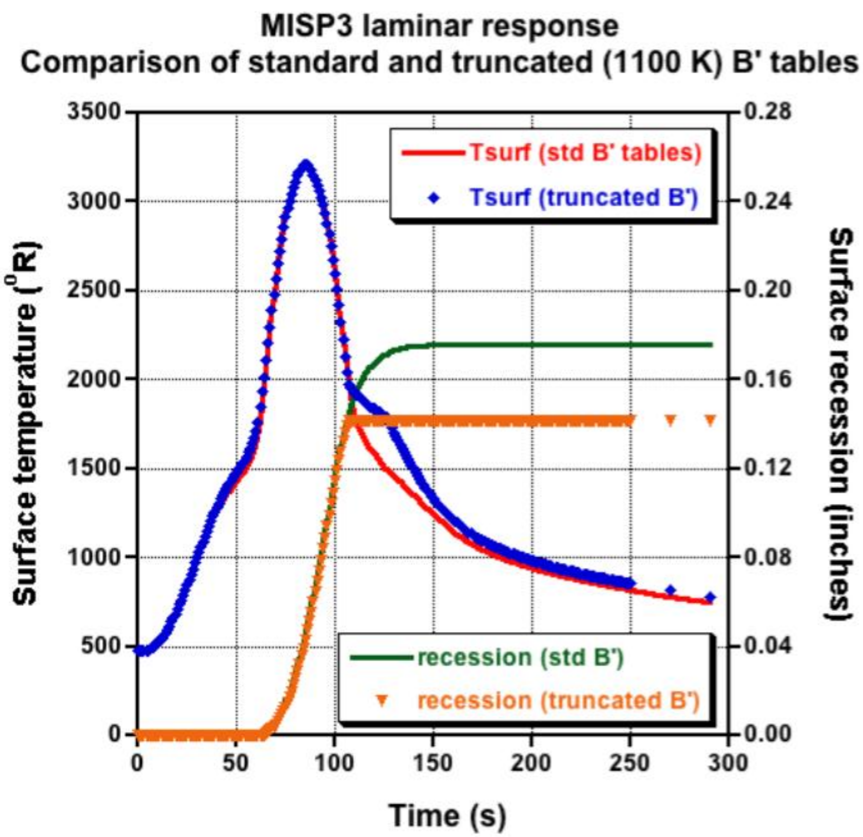


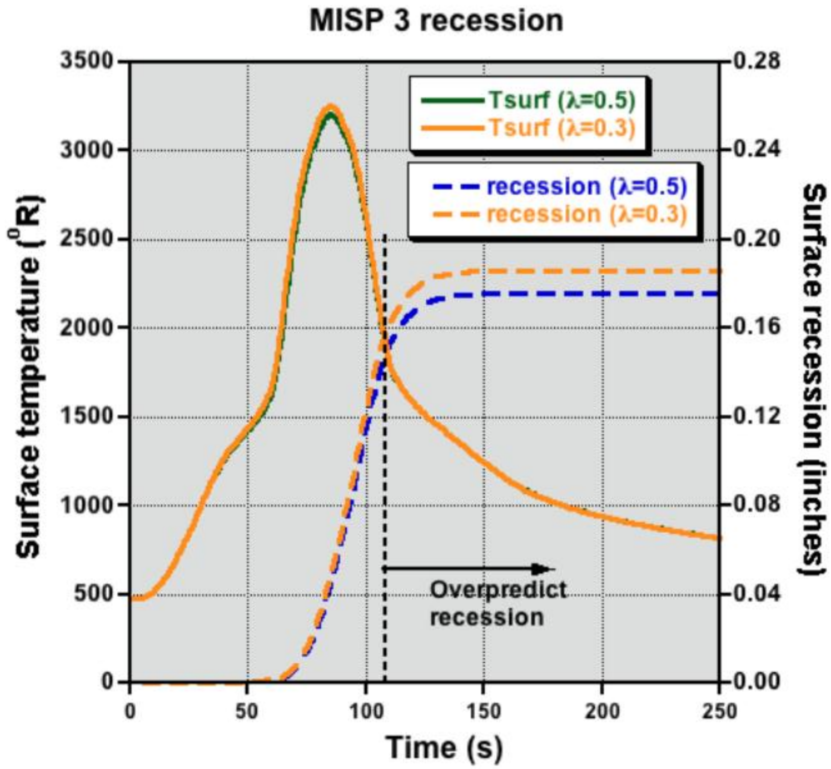


- **Mass benefit is about 1lb per degree**
- **Becomes Nonlinear**

Entry Systems and Technologies Division

Material Response Empirical Approximations





1. Left: Modified B' tables to account for finite rate chemistry effects (non-equilibrium) at low temperatures
2. Right: Blowing correction, λ (blown/unblown heat transfer coefficient)

Entry Systems and Technologies Division

Outline

- Introduction to Heat shield design
- Motivation for Statistics based HS design
  - Application of TPS Standardized Policy
  - Mission Risk and Reliability Requirements
- *UQ for TPS Thermal Sizing Margin Management Process*
  - *Margins, Rationale and Sensitivity Trades*
  - *Thermal Margin*
- **UQ and Statistical Engineering for Flight Data Reconstruction**
  - **Stardust**
  - **MEDLI**
- Conclusions

Designing STARDUST today

	Stardust PICA Model+SD margins	Current PICA Model +SD margins	Current PICA Model-SAMPLE RETURN	Current PICA Model-HUMAN RATED
Case	Stardust-Original design	Stardust	CEV-margin	Stardust sizing with all CEV trades
Trajectory Dispersed	**1.88**	**1.04 (45%↓)**	**1.04**	**1.52 (19%↓)**
Aerothermal Margined	2.27	1.26	1.11	1.55
Thermal Margined (Material Properties)	2.26	1.25	1.21	**2.17**
Baseline Thickness, T_b	2.43	1.34	1.23	2.42
Recessed Thickness, ΔT_{Rec}	-	-	0.17	0.17
1.1 x T_b	-	-	1.35	2.66
$T_b + \Delta T_{R\text{-}margin}$	-	-	1.39	2.59
Final Thickness	**2.29**	1.22	1.39	**2.66**
Margined-Unmargined	0.41	0.18	0.35	1.14

0.6

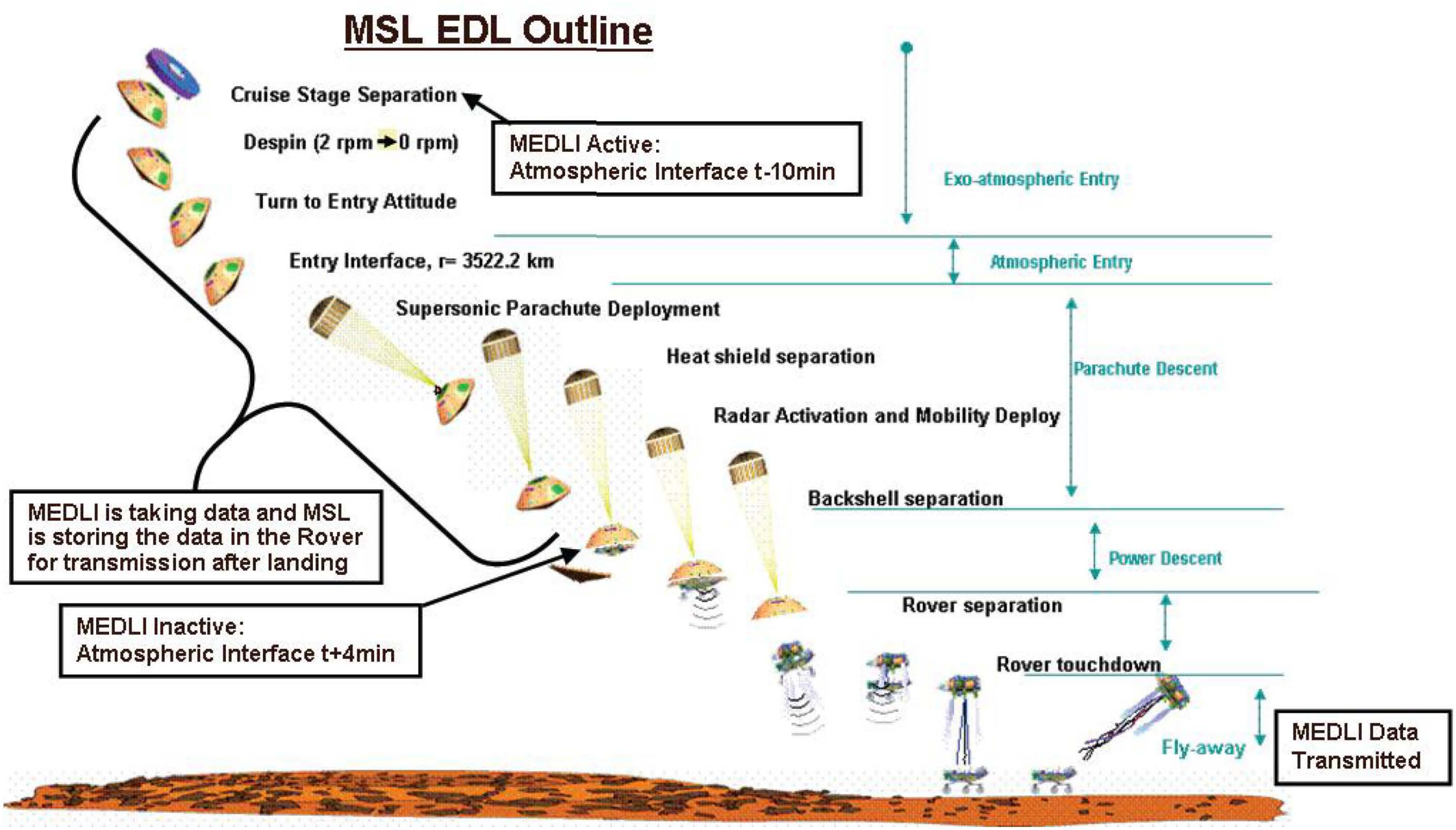
0.9

MEDLI BACKGROUND

- MEDLI
  - stands for MSL Entry Descent and Landing Instrumentation
  - it is an Entry Descent and Landing (EDL) instrumentation suite flying on Mars Science Laboratory (MSL) launching in November 2011

- This is the most instrumented heat shield to Mars, and will provide the largest EDL engineering dataset ever returned from Mars

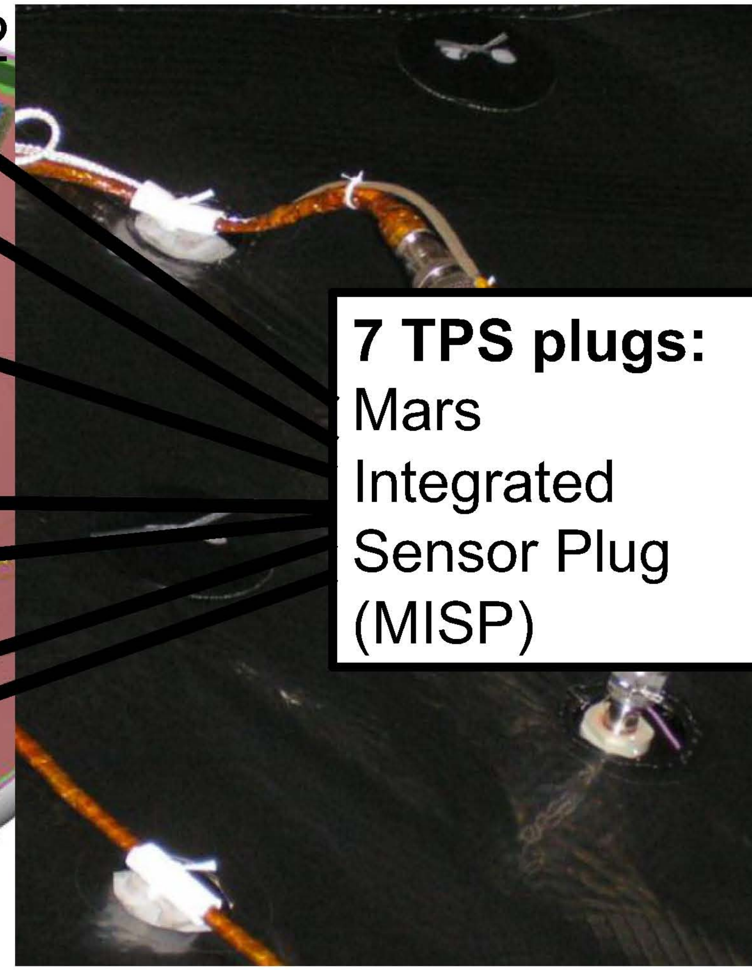
MEDLI Activity during EDL Sequence



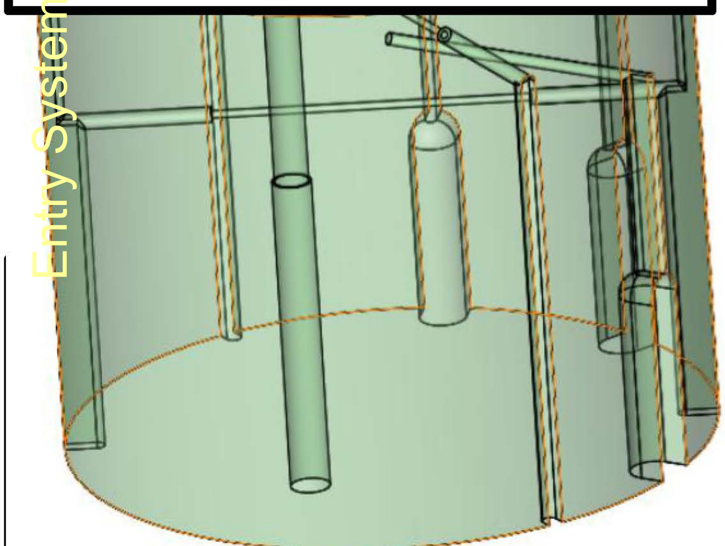
MEDLI Instrumentation on MSL Heat Shield

Entry Systems and Technologies Division

Sensor Support Electronics: provides power to sensors, conditions/digitizes sensor signals



7 TPS plugs: Mars Integrated Sensor Plug (MISP)



MEADS=M

MEADS=Mars Entry Atmospheric Data System
MISP = Mars Integrated Sensor Plug
TC = Thermocouple
HEAT = isotherm location with depth

Aerothermal and TPS Objectives

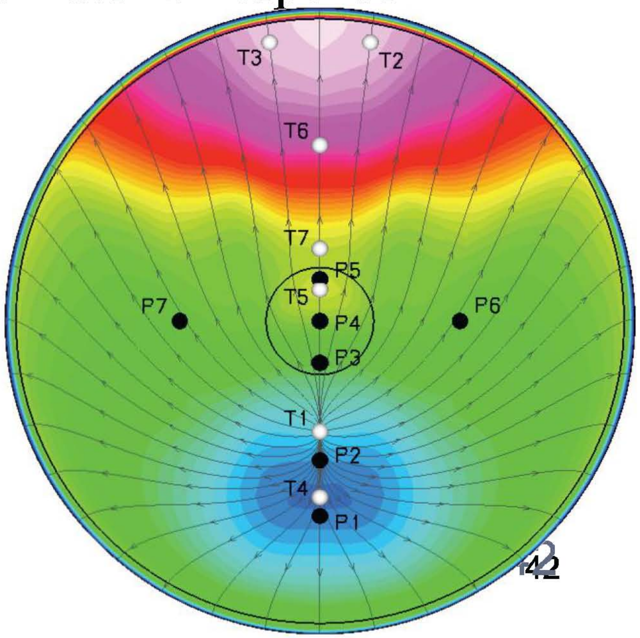
Objective 1: Measure sub-surface TPS thermal response as a function of time by direct measure using thermocouples embedded in each MISP in the heatshield (T1 through T7)

Objective 2: Measure TPS recession as a function of time using the calibrated response of the HEAT sensors following an isotherm trace (extrapolates ground test results to flight)

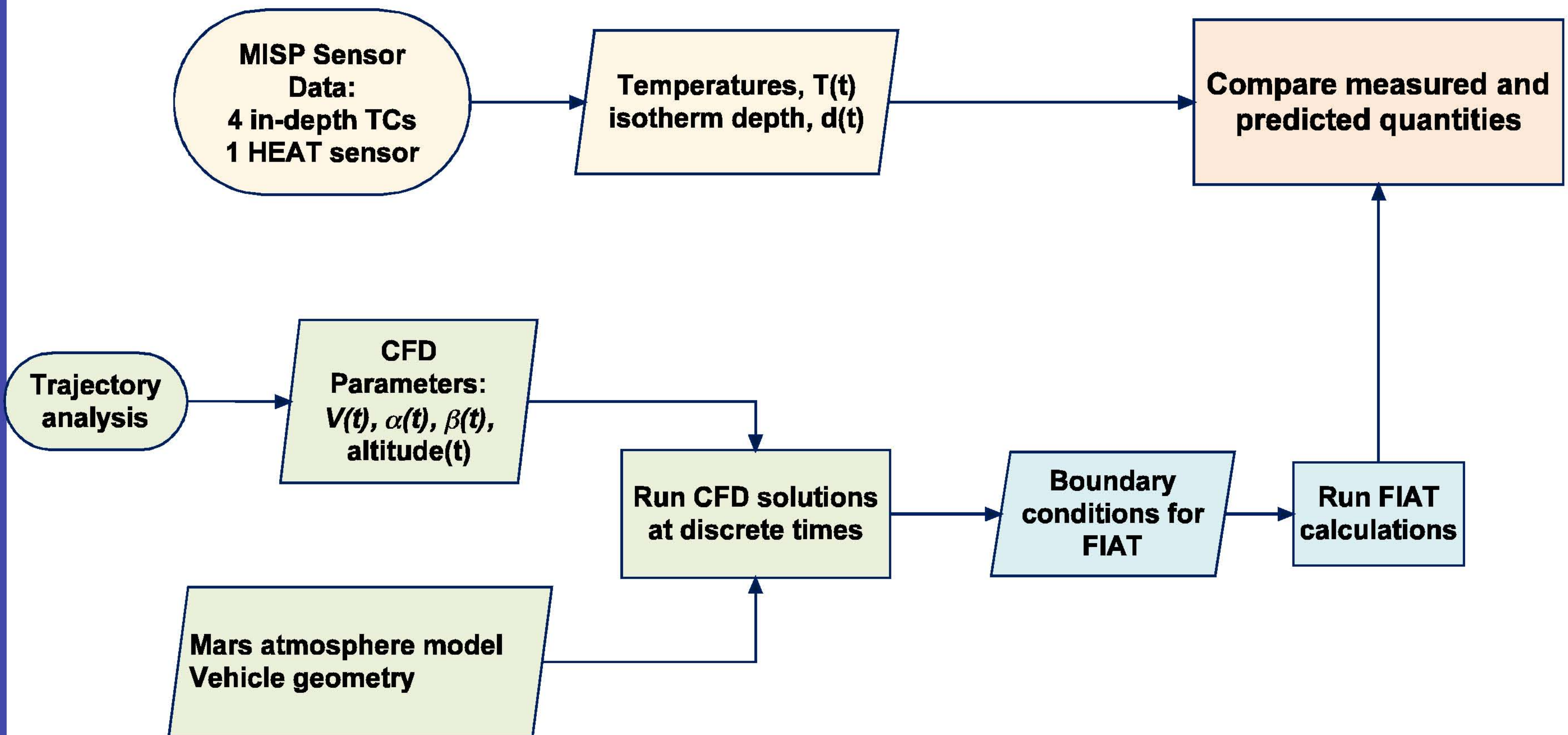
Objective 3: Obtain information about the distributed aerothermal heating on the heat shield as a function of time indirectly by assessing the aerothermal environments necessary to have produced the observed material response

Additional benefits

1. Determine catalytic heating effects
2. Determine the time of transition to turbulence
3. Determine whether augmented heating above nominal laminar levels occurs in the flow stagn ation region



MISP Reconstruction Overview



- Direct comparison of predicted and measured quantities (currently procedure assumes no iterative CFD-FIAT process after the initial comparison)
- Predictor-corrector iterative method –in progress
- Inverse Parameter Estimation technique –in progress

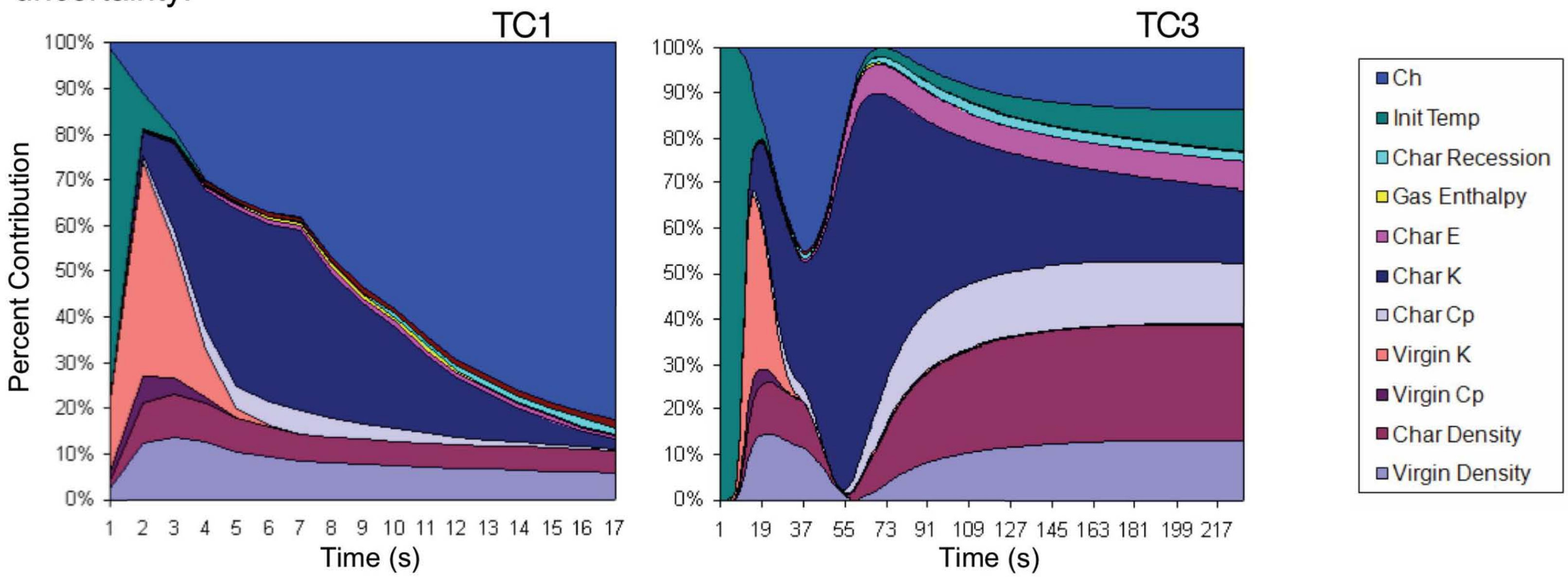
Inverse Parameter Estimation Method

$$\mathbf{Y} = \mathbf{T} + (\varepsilon_{random} + \varepsilon_{bias}) = \mathrm{G}[\mathbf{P}_{true}] + \varepsilon_{model}$$

Y = Data
T = True Response
ε = Error
G = Physical Model (FIAT)
P = Parameters

1. Uncertainty Analysis (identify parameters w highest uncertainty contribution)

2σ uncertainty values are assigned to aerothermal variables and material properties. A **FIAT Monte Carlo** simulation is performed to determine the contribution of the input parameters to the predicted temperature uncertainty.

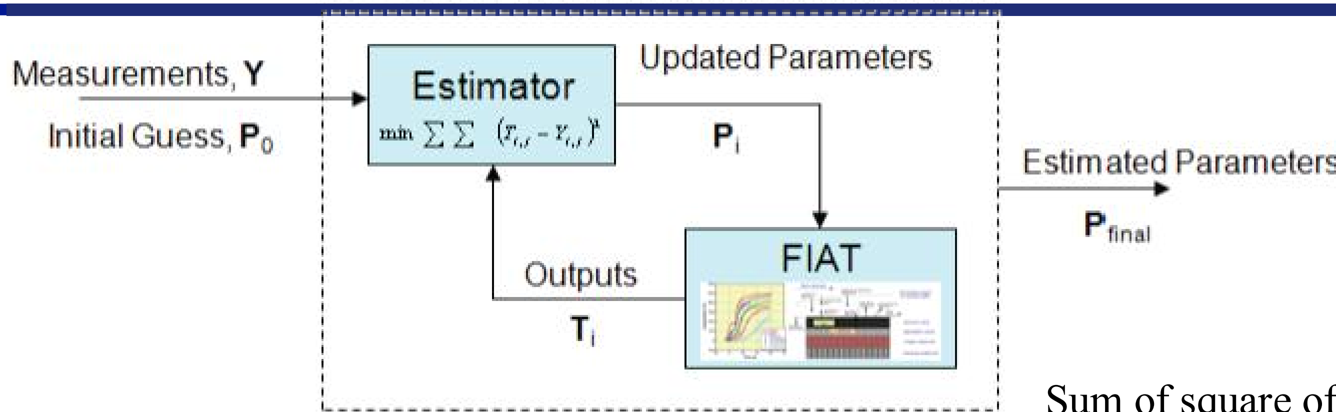


Top uncertainty contributors are C_h, Cp_v, Cp_c, ρ, κ_v, κ_c, ε_c

2. Sensitivity Analysis (identify correlations between parameters):

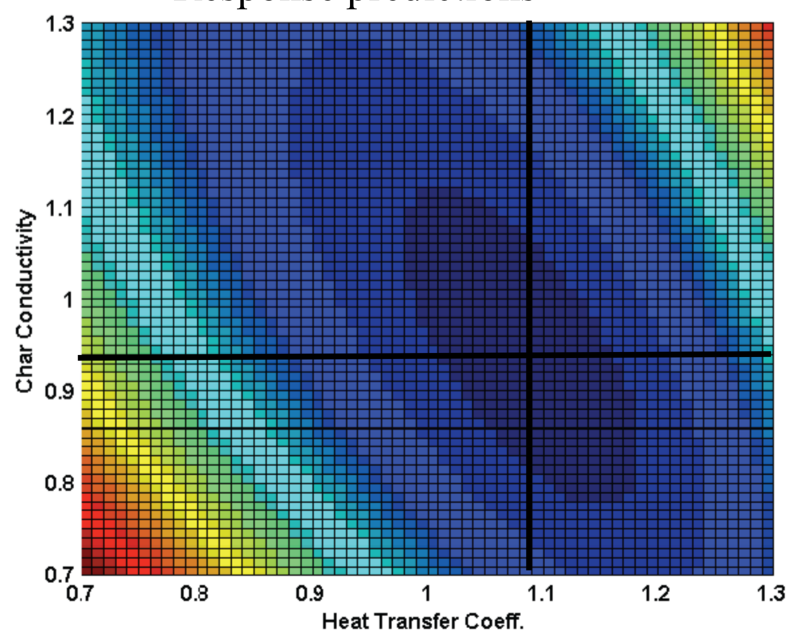
In inverse analysis, parameters with high correlation are difficult to estimate simultaneously (C_h and ρ, C_p and κ)

Inverse Parameter Estimation Method



- The Inverse Parameter Estimation (IPE) code wraps around FIAT and estimates scaling factors of the <u>input parameters</u> to match measured data via an optimization procedure.
- Code verification
  - Recovers parameters back to the nominal values if starting at a random initial guess
  - Converges to the mathematical minimum of the sum of squares of errors with the experimental data
- Code validation: ArcJet MSL PICA test
- Challenges:
  - Solution existence, uniqueness and process stability
- Minimize errors: ε_{model}, ε_{random}, ε_{bias}

Sum of square of errors between measurements and Material Response predictions



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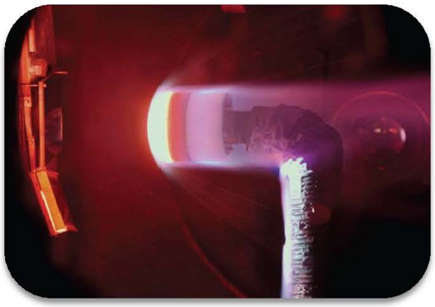
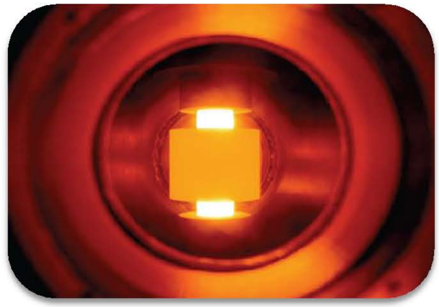
Theory and Experiments need to team

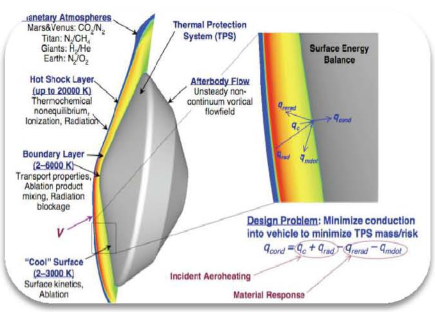


ArcJet tests

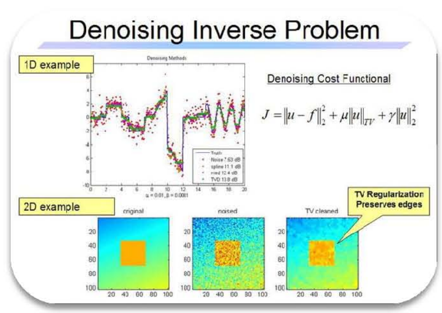


Material Property Tests

Other lab tests



Modeling and Tools



UQ, SE, Optimization and IPE

Conclusions

- NASA has invested significant resources in developing and validating a mathematical construct for TPS margin management:
  - Tailorable for low/high reliability missions
  - Tailorable for ablative/reusable TPS
- Uncertainty Quantification and Statistical Engineering are valuable tools not exploited enough
- Need to define strategies combining both Theoretical Tools and Experimental Methods
-
- There’s plenty of room at the “TOP”

The main reason for this lecture is to give a flavor of where UQ and SE could contribute and hope that the broader community will work with us to improve in these areas…