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A Monte Carlo based Thermal Margin Derivation for Flight Environments

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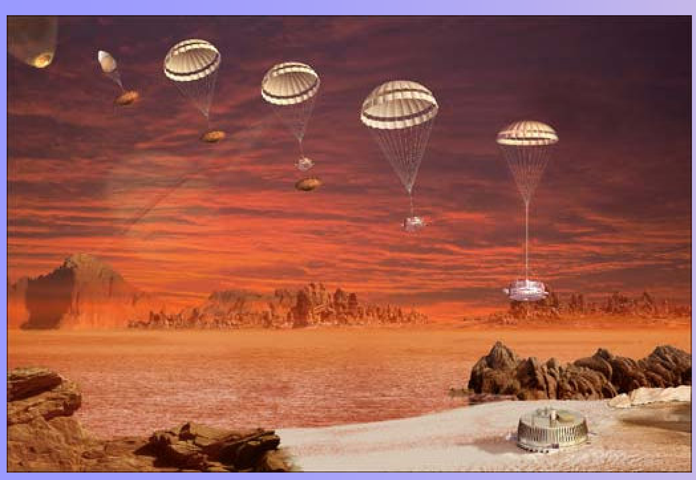
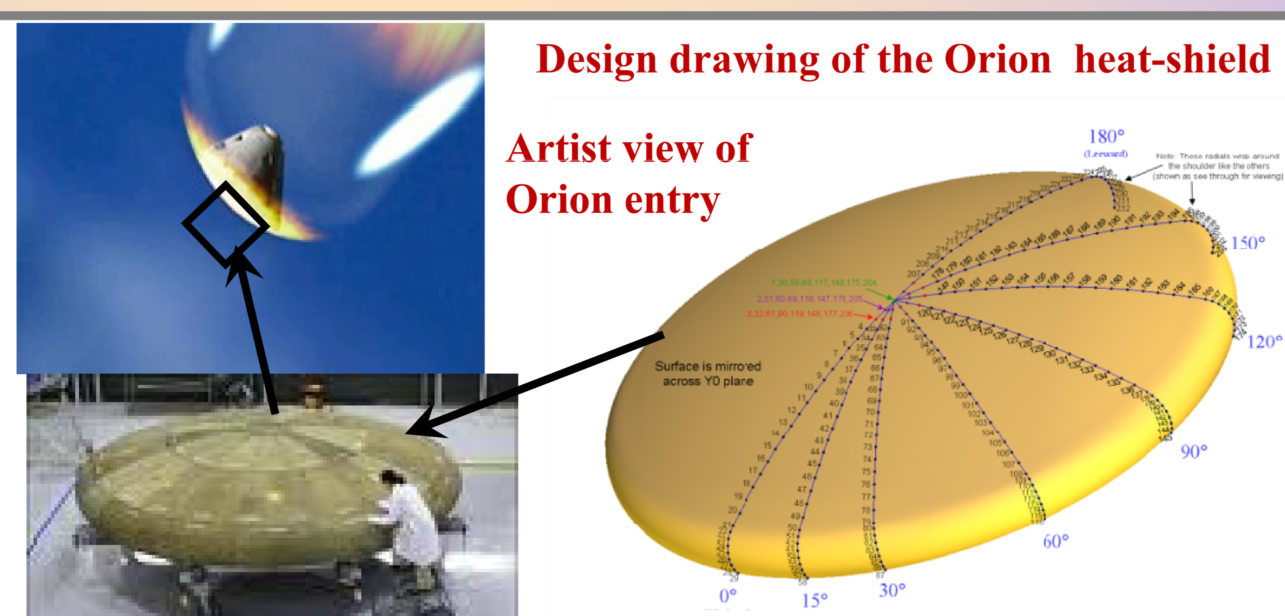


CONTEXT & OBJECTIVE

- A reentry vehicle using Thermal Protection System (TPS) technology for heat management is required to pass through <u>a sizing evaluation process</u>
- The inherent various uncertainties and biases occurring throughout this process are applied within a procedure to ensure that the final design TPS thickness represents the sum of the nominal and <u>margin component</u>
- <u>Thermal Margin</u> is the variation about the BONDLINE and/or structural interface temperature limits as defined by the uncertainties in the material properties characteristic to the TPS and ground to flight traceability.
- Thermal Margin should satisfy the mission-specific design requirement of maintaining the bondline temperature; its quantification relied on expert opinion so far



Design drawing of the Orion heat-shield

Artist view of Orion entry

Orion PICA heat-shield

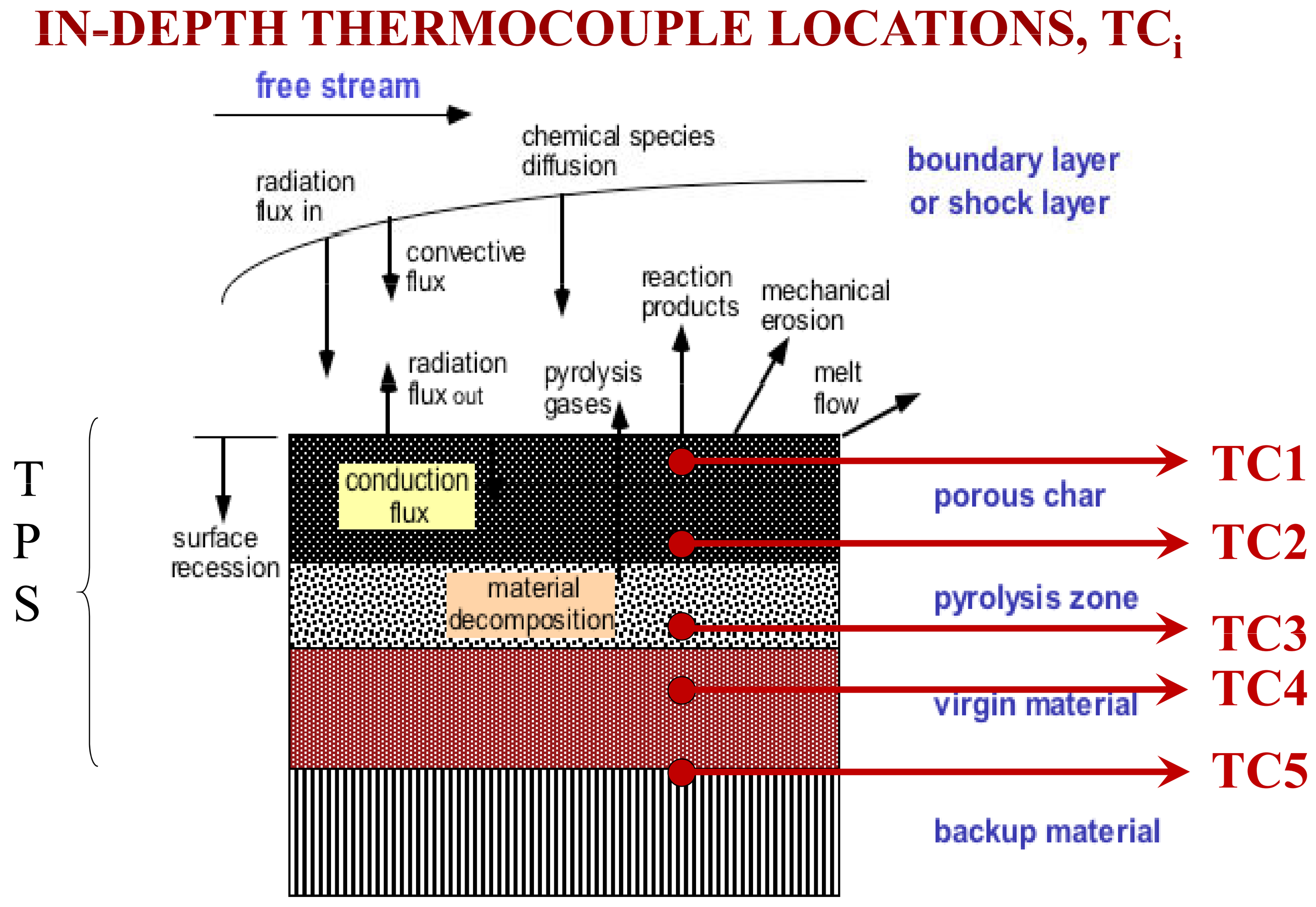
TARGET MISSIONS: CEV, MSL, small probe missions

- ✓Establish mathematical procedure to derive thermal margin using Monte Carlo statistical analysis
- ✓Anchor ablation model using measured temperatures (thermocouple) during Arc Jet tests
- ✓Monte Carlo material properties uncertainties on Arc Jet conditions for Bondline Temperature distributions
- ✓Monte Carlo material properties uncertainties on flight conditions for Bondline Temperature distributions

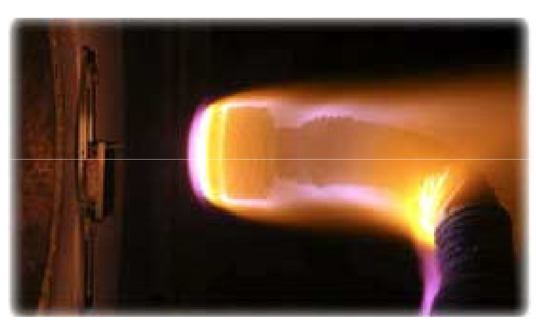
ABLATION MODEL ERROR CALCULATION

$$\theta_{AJ} = \left(T_{design} - T_{init}\right)\cdot 3\sigma_{data}$$

ABLATION MODEL PREDICTION FOR VARIOUS IN-DEPTH THERMOCOUPLE LOCATIONS, TC_i

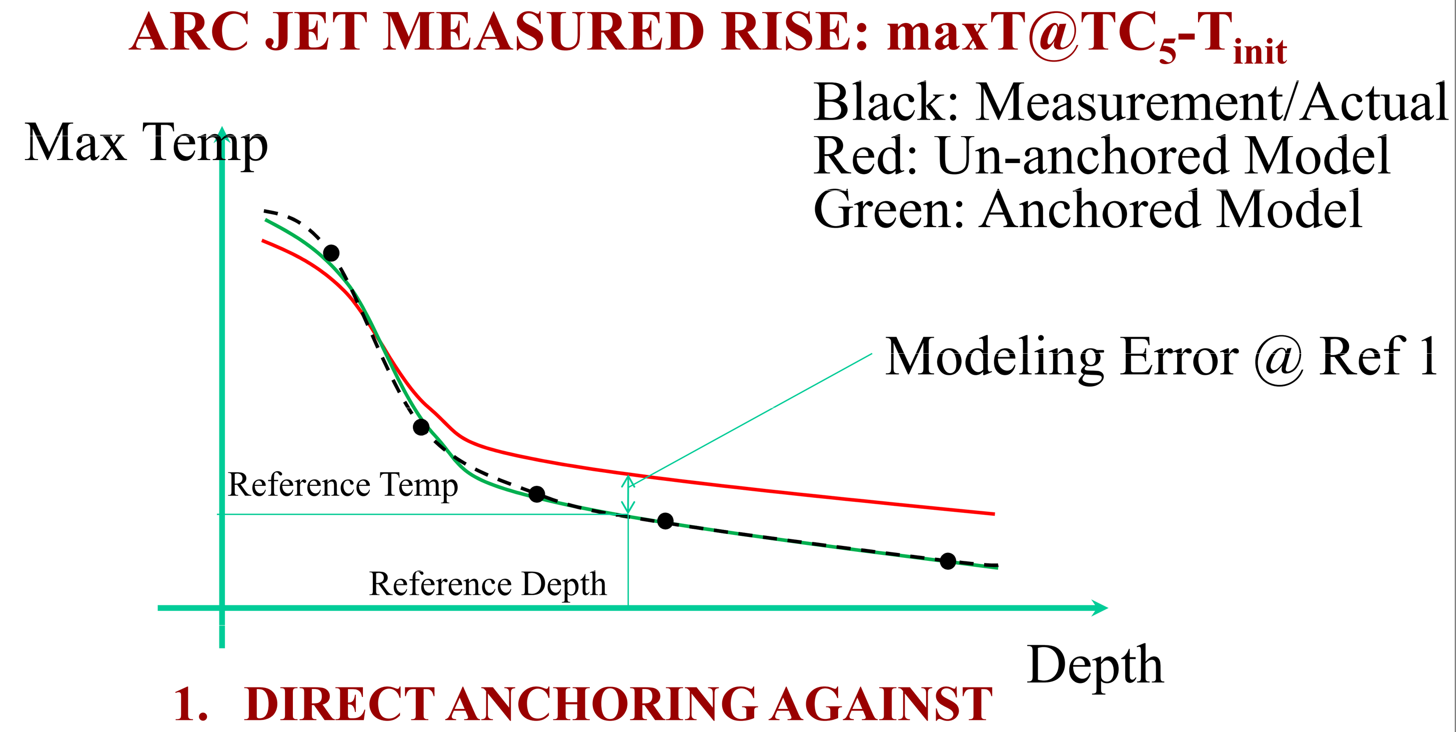


CALCULATED MEASURED RISE: $maxT@TC_5-T_{init}$



Avcoat
12 samples
Mean error = 18%, σ = ±15%
Inferred Thermal Margin θ_{AJ}= 228°F
Exclude samples with error>40%
Mean error = 12%, σ = ±9%
Inferred Thermal Margin θ_{AJ}= 146°F

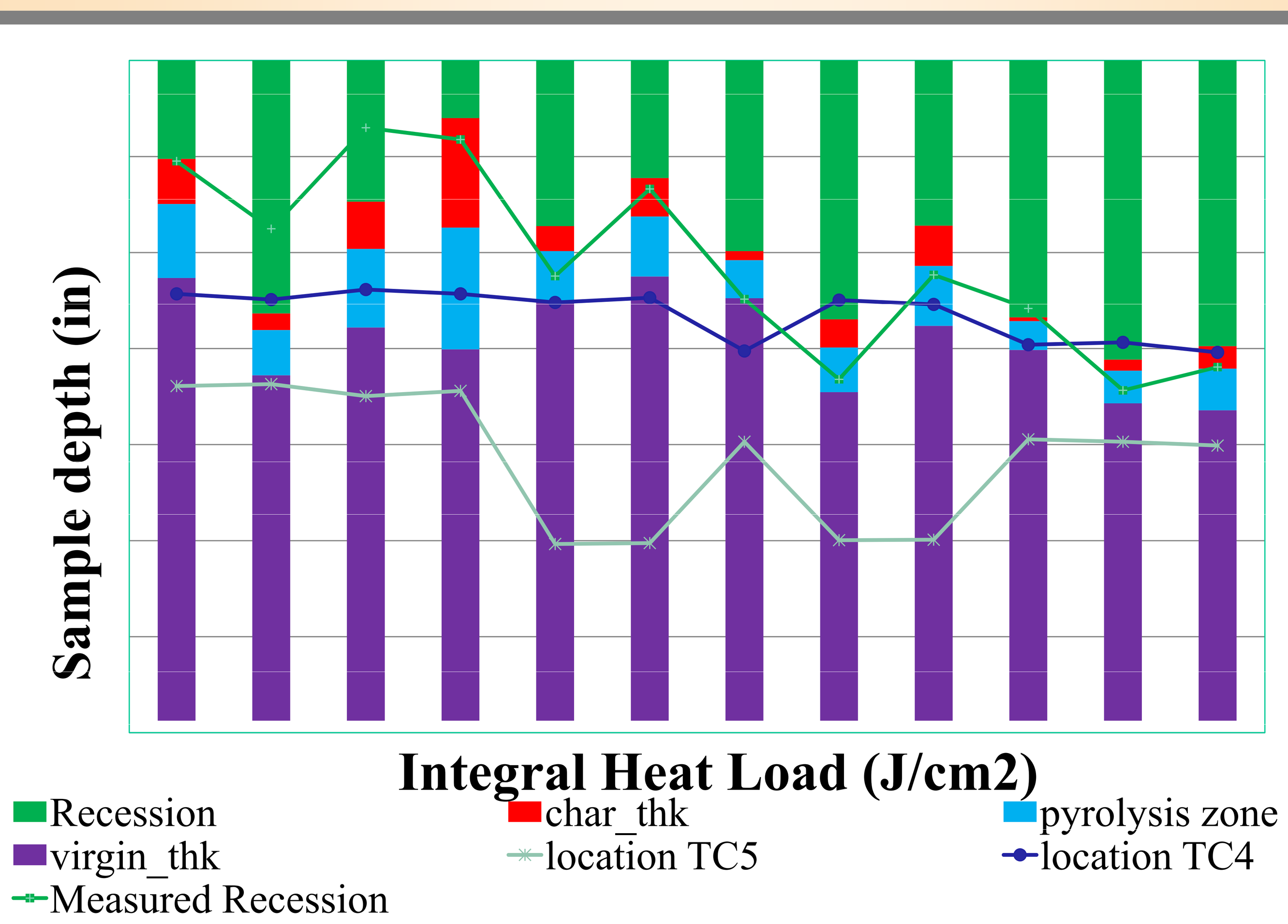
ARC JET MEASURED RISE: $maxT@TC_5-T_{init}$



1. DIRECT ANCHORING AGAINST THERMOCOUPLE DATA
2. IN-DEPTH TEMPERATURE BASED ANCHORING

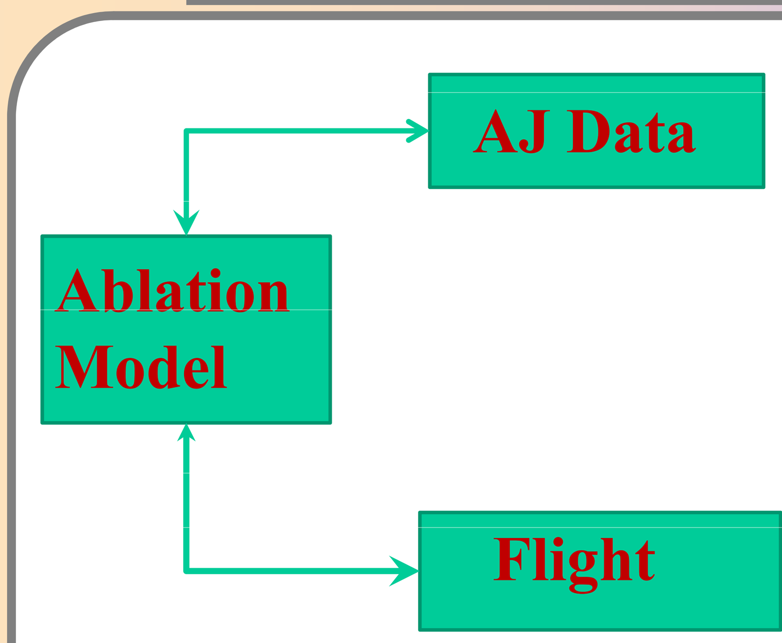
PICA:
52 samples
Mean error = 8%
3σ Deviation = ±26%
Inferred Thermal Margin θ_{AJ}= 100°F

MONTE CARLO STATISTICAL ANALYSIS



- ✓ Location of TC at which model error is calculated needs to be in the virgin material to capture the effect of uncertainties in material properties
- ✓ Sufficient sampling for 3-sigma level development of thermal margin
- ✓ Correct implementation of material properties correlations in Monte Carlo analysis
- ✓ Sampling
- ✓ Monte Carlo code validation and verification required

THERMAL MARGIN DERIVATION



Model error: σ_{data}

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

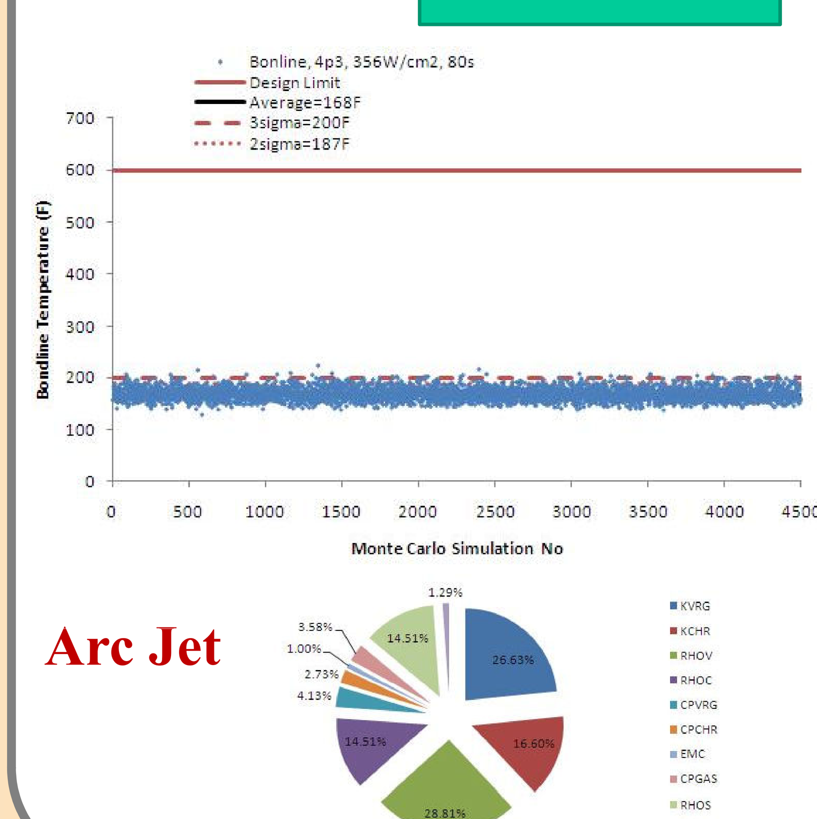
$$TM = (T_{design} - T_{init}) * \sigma_{data} * \frac{\sigma_{flightBL}}{\sigma_{groundBL}}$$

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

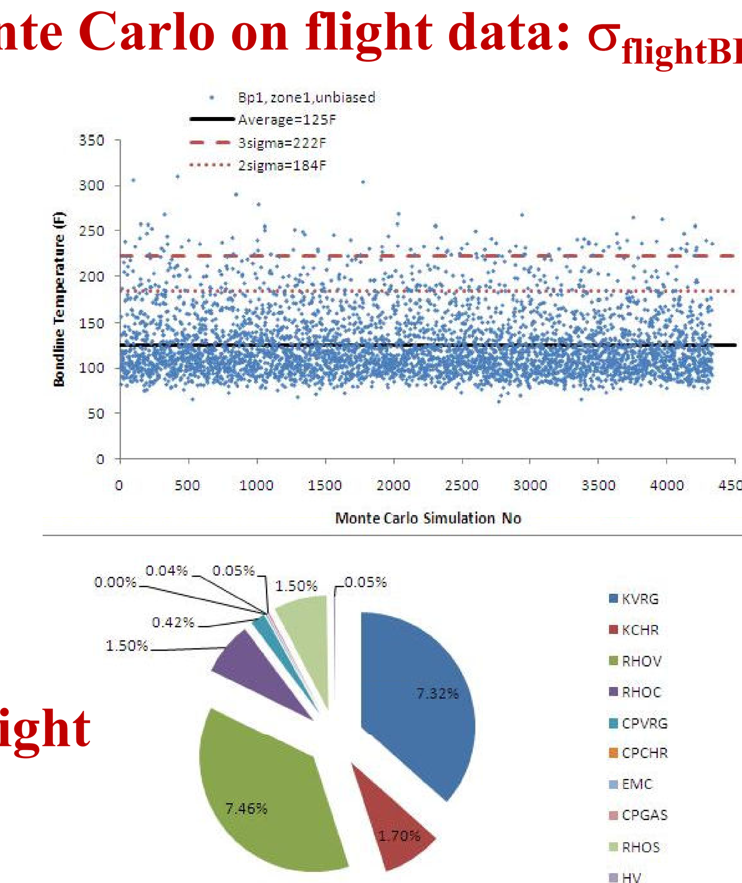
$$TM = (T_{design} - T_{init}) * \sigma_{flightBL}$$

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

Arc Jet



Flight



CONCLUSION & OUTLOOK

- current results for CEV and MSL indicate that the rigorous process produces results that are in family with prior more empirical approaches
- rigorous margin analysis is still under development, and requires a well thought out ground test program, with obtaining statistical data as a priority, to be effective.
- better margin definition has the potential of significantly reducing TPS mass and/or increasing TPS reliability. As importantly, it will arm the system engineer with a tool to make quantified, justifiable mass trades between TPS thickness and other reliability improvement strategies.