A Reliability Comparison of Classical and Stochastic Thickness Margin Approaches to Address Material Property Uncertainties for the Orion Heat Shield

AIAA SciTech 2018

Steve Sepka
Jeremy Vander Kam
Kathy McGuire

January 10, 2018

Order of Presentation

- Background
- Motivation/purpose
- List input values and assumptions
- Procedure
- Example analysis for one body point
- Summary of results
- Conclusion

Background

Orion TPS I/O

A spaceship's planetary Entry, Descent, and Landing (EDL) is comprised of three major components:

- Guidance, Navigation, and Control (GNC)
- Aerothermodynamics
- Heat Shield Thermal Protection System (TPS) material response

Each of these components is considered a "branch" of EDL

We can find the nominal TPS thickness by using nominal values in each branch

But what about uncertainties?

How much extra TPS – **Margins** – is needed?

Background

Orion TPS I/O

To find the Margins, NASA currently uses an root-sum-square technique that has separate components for each branch of the EDL process

Baseline Margin =

$$\text{nominal TPS thickness} + \left[(\text{extra TPS} - \text{nominal TPS})^2 + (\text{extra TPS} - \text{nominal TPS})^2 + (\text{extra TPS} - \text{nominal TPS})^2 \right]^{1/2}$$

- (extra TPS – nominal TPS)^2: GNC uncertainty
- (extra TPS – nominal TPS)^2: aerodynamics uncertainty
- (extra TPS – nominal TPS)^2: material response uncertainty

Background

How do we find TPS thickness?

- TPS material response codes are used - they find the TPS thickness needed so that the adhesive bond temperature does not exceed its use temperature
- Some TPS response codes are FIAT (Fully Implicit Ablation and Thermal Response Code) and CHAR (Charring Ablating Thermal Protection Implicit System Solver)
- NASA Ames has developed monte carlo applications of these codes: **mcFIAT** and **mcCHAR**

Background

- How do we find extra TPS thickness due to material uncertainty branch?
- The extra TPS due to material uncertainty is found by reducing the not to exceed the Avcoat/EA9394 interface temperature from 260°C to 200°C
- This 60°C reduction in NTE is called the Bondline Temperature Material Margin, BTMM, and is applied at each body point location on the forebody heat shield.
- Using the nominal sized thickness at a body point, 10,000 monte carlo CHAR runs find the maximum bond line temperature (mBLT) **dispersion** about the nominal 260°C
- We vary only material properties since this RSS "branch" considers only material property uncertainty
- Using Gaussian statistics, we take 60°C/SD to find the confidence interval of the 60°C BTMM: is it 1σ, 2σ, …. for this body point location?

Motivation/Purpose

What is the confidence (1σ, 2σ, etc.) of the 108°F (60°C) Bond Line Temperature Material Margin (BTMM) currently used in the Orion RSS sizing process?

Knowing the confidence interval will give NASA assurance on its margin sizing process

mcCHAR Setup

Monte Carlo Settings - TPS

Orion TPS I/O

Uncertainties expressed as 2 x CoV (standard deviation / mean) unless otherwise noted
(**pyrolysis gas enthalpy is scaled the same as char thermal conductivity**)

Material Properties		
Initial temperature [K]	280.928-307.594	uniform
Initial surface pressure	0	
Top TPS (Avcoat)		
Specific heat capacity, virgin	0.04	
Specific heat capacity, char	0.04	
Thermal conductivity, virgin	0.08	
Thermal conductivity, char	0.18	
Density, virgin [kg/m^3]	570.2573-629.5256	uniform
Density, char	0.07	
Absortivity, virgin	0	
Absortivity, char	0	
Thickness, max additional [m]	0.000508	added
Permeability	0	
Klinkenberg slip parameter	0	
Porosity	0	
Emissivity, virgin	0	
Emissivity, char	0	
Heat of formation, virgin	0	
Heat of formation, char	0	
Decomposition (each component)		
Pre-exponential factor	0.109 0.179 0.188	
Reaction order	0.263 0.388 0.236	
Activation temperature	0.060 0.061 0.033	

B'tables		
B'c	0.15	
Wall enthalpy	0.10	
Density	0.04	
Molecular weight	0.04	
Roughness		
Roughness height	~~0.487~~	not used
Height offset (constant)	~~-0.000223~~	
Substructure		
Thickness, adhesive [m]	0.000254-0.000762	uniform
Thickness, composite	+/-0.000127	5 mil tolerance
Density	0.02	
Specific heat capacity	0.02	
Thermal conductivity	0.02	

Red = parameters used in this study

These values are found from "Determination of Uncertainties for Analytically Derived Material Properties to be used in Monte Carlo Based Orion Heatshield Sizing" SciTech 2018 Session TP-03 Monday AIAA-2018-0499 Scott Coughlin, *Sixel William; Steven Sepka, Mary K. McGuire*

CHAR Set-up

- **Avcoat model**
- **Two Trajectories:**
  - guided
  - ballistic/abort
- **Stackup: Avcoat + 0.015" EA9394 + (bp dependent)" T300-EX1505**
- **Initial and re-radiation temperature: 21.1°C**

Procedure

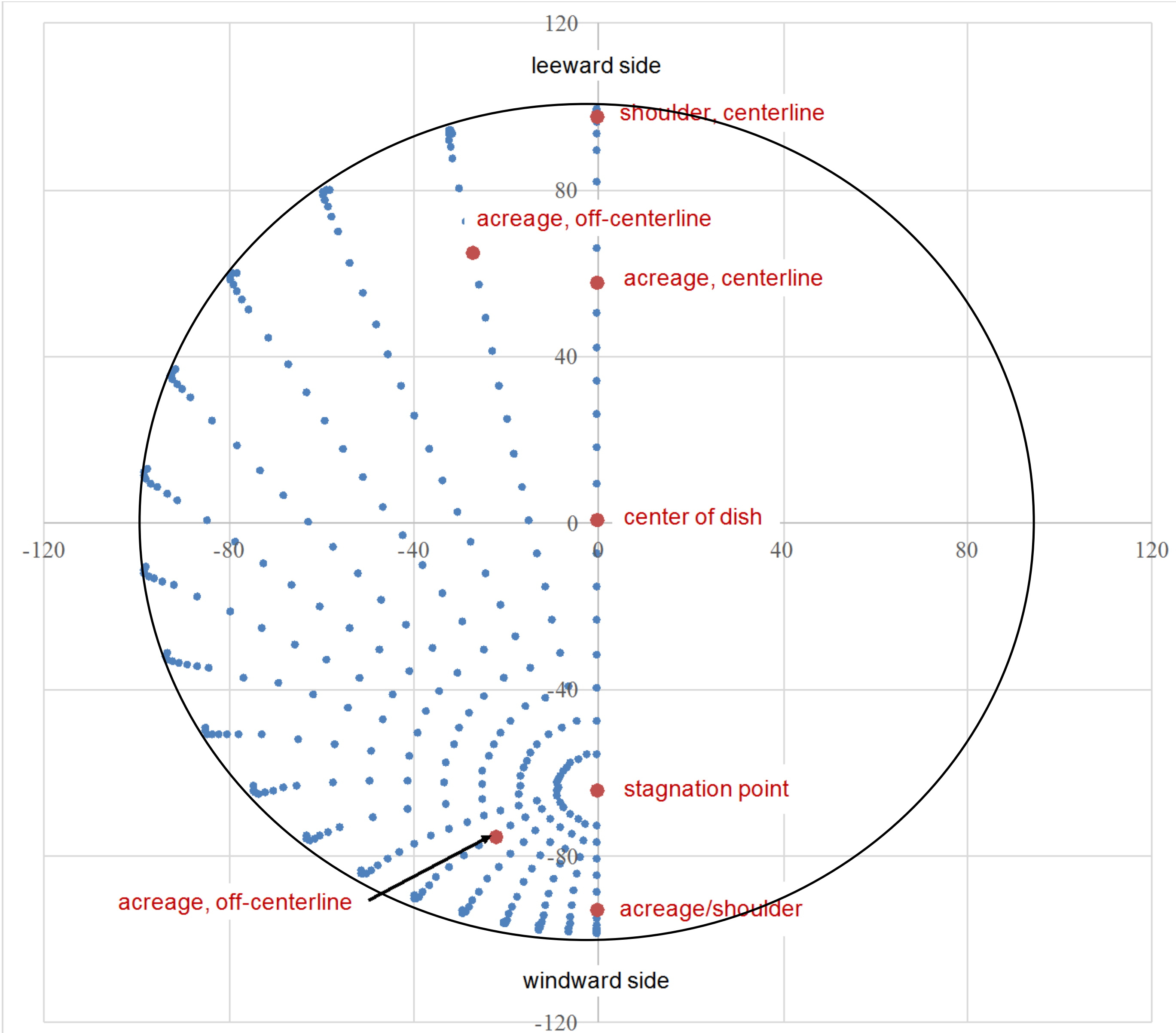
Procedure

Seven body points were selected. For each one:

1. Choose the nominal guided or ballistic/abort trajectory.
2. Determine nominal Avcoat thickness using CHAR: 260°C peak Avcoat/EA9394 bond line temperature
3. 10,000 mcCHAR runs using nominal Avcoat thickness (analysis mode) and varying only material properties
4. Data analysis includes bond line temperature and recession dispersions, correlation studies, and confidence level of 108°F (60°C) BTMM

Body Point Locations

Orion TPS I/O



How Are The Data Analyzed?

Orion TPS I/O

At each body point location:

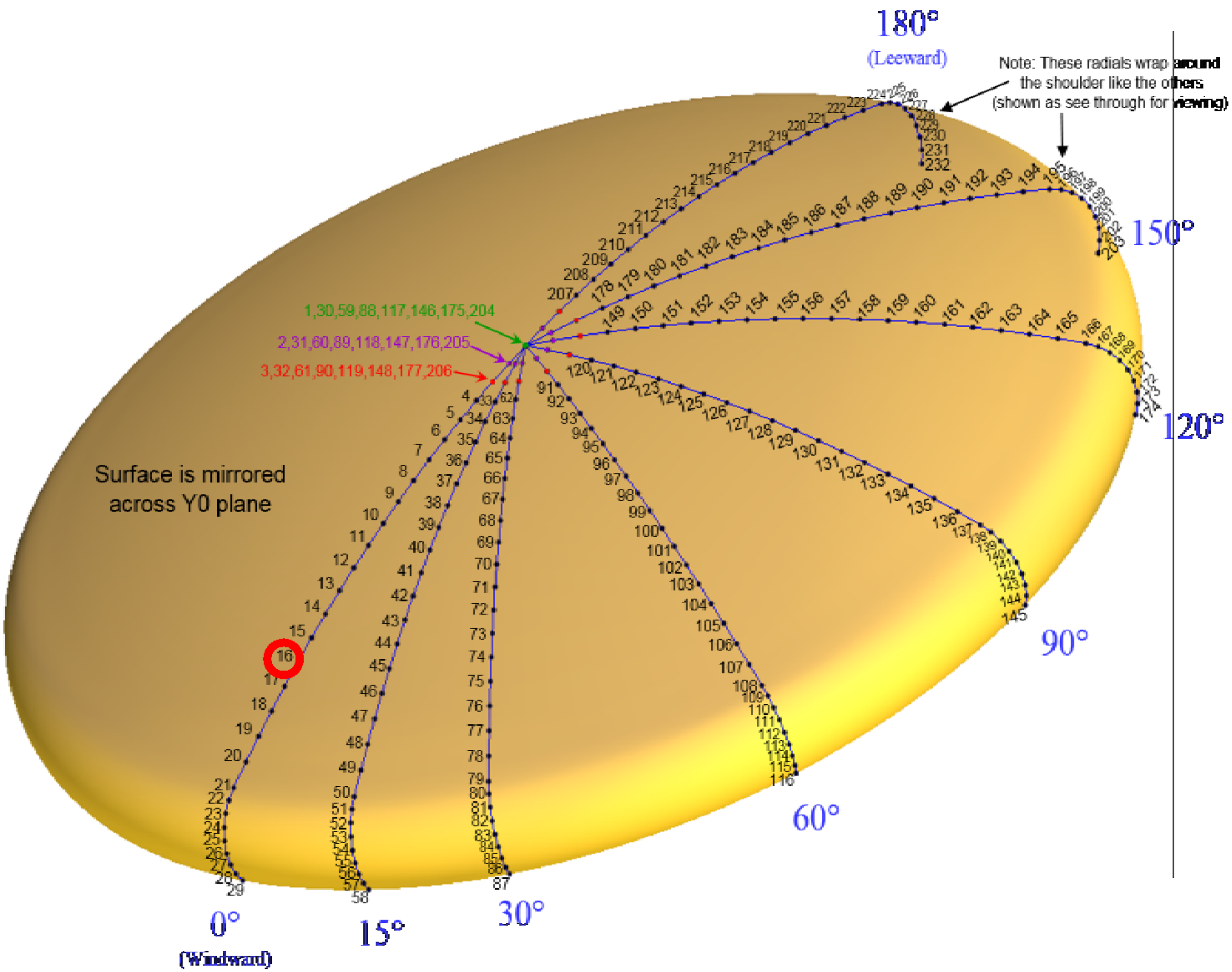
- Maximum bond line temperature (mBLT) and recession dispersions
- Gaussian statistics
- Correlation plots

Note: pyrolysis gas enthalpy is scaled the same as char thermal conductivity and for correlation studies is not included in the analysis

$$60°C/SD(°C) = \text{Confidence Interval } (\sigma)$$

Example of the analysis – stagnation point

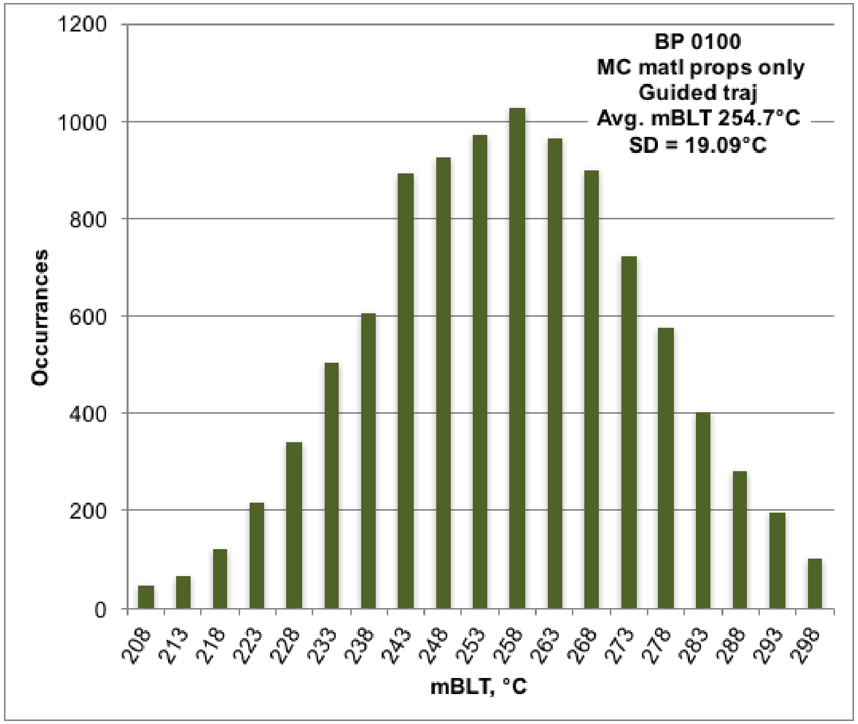
Orion TPS I/O



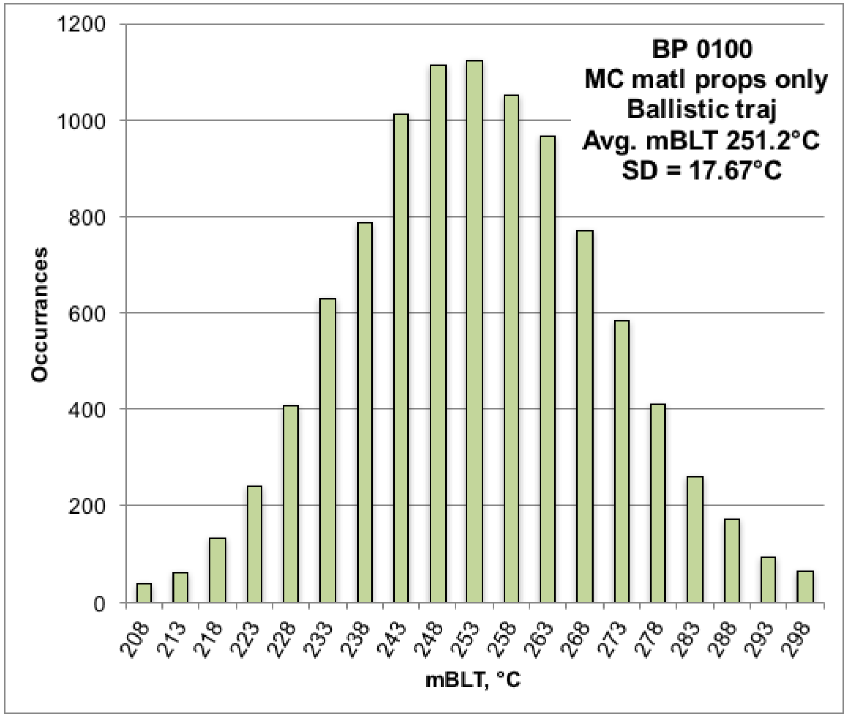
Stagnation Point mBLT Dispersion

Orion TPS I/O

Guided



Ballistic

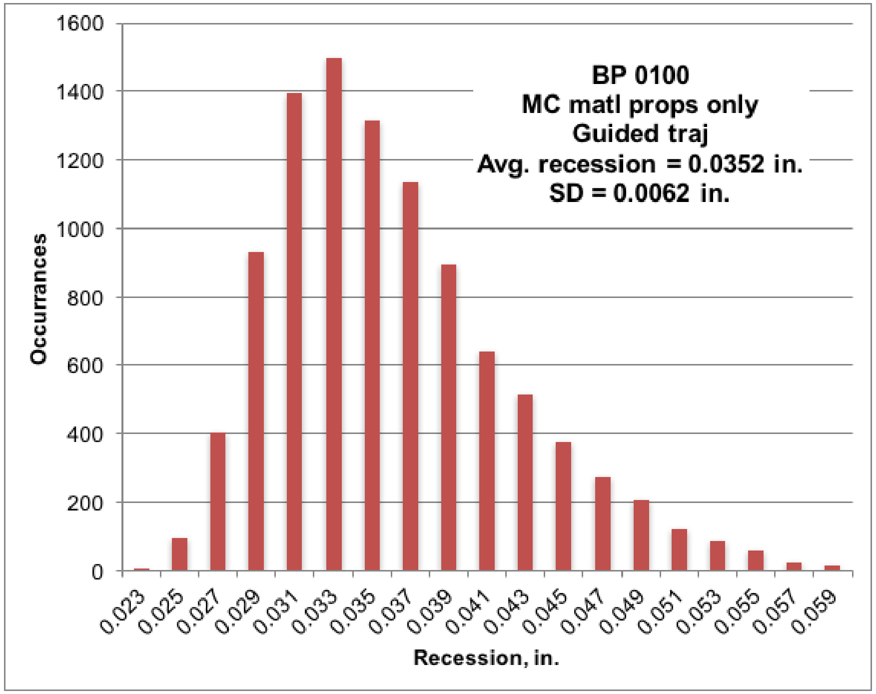


mBLT = maximum bond line temperature

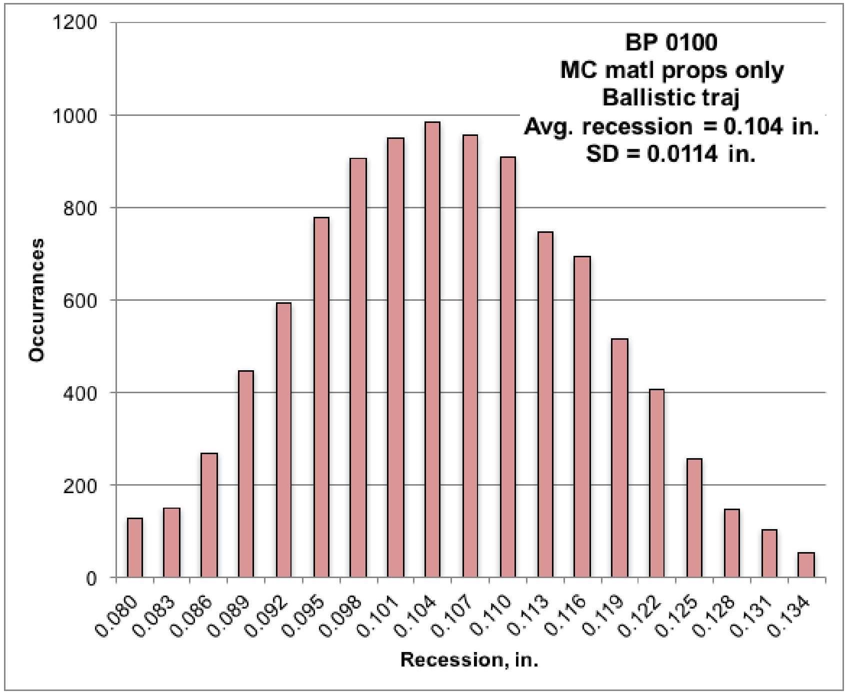
Stagnation Point Recession Dispersion

Orion TPS I/O

Guided



Ballistic



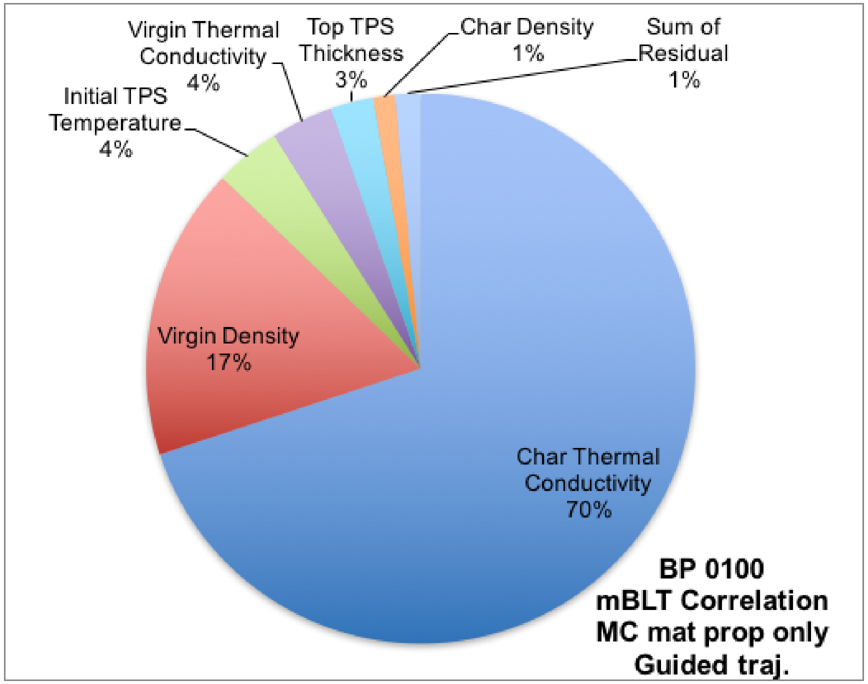
Stagnation Point mBLT Correlation

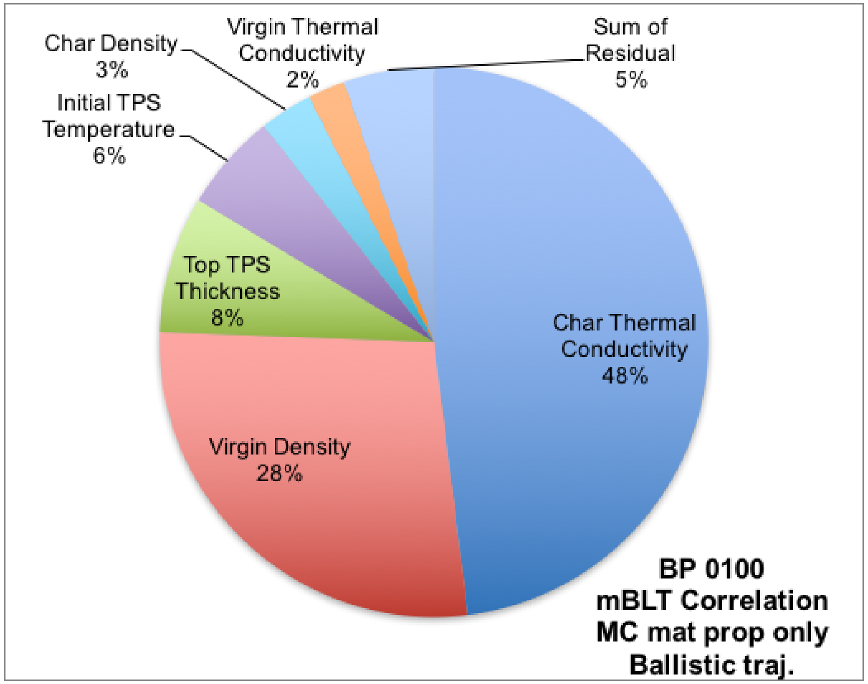
Orion TPS I/O

Guided

$$Correl(X,Y) = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}}$$

Ballistic





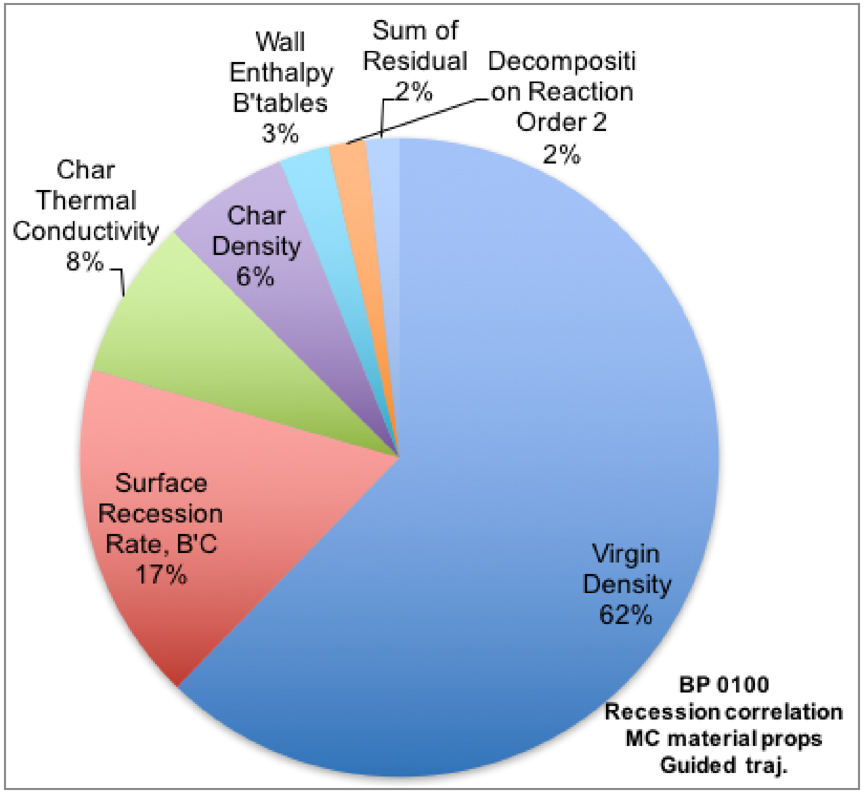
item	CorCoeff	CCsquared
Char Thermal Conductivity	0.836	0.699
Virgin Density	-0.415	0.172
Initial TPS Temperature	0.197	0.039
Virgin Thermal Conductivity	0.191	0.036
Top TPS Thickness	-0.159	0.025
Char Density	0.113	0.013

item	CorCoeff	CCsquared
Char Thermal Conductivity	0.693	0.480
Virgin Density	-0.525	0.275
Top TPS Thickness	-0.284	0.081
Initial TPS Temperature	0.240	0.057
Char Density	0.177	0.031
Virgin Thermal Conductivity	0.148	0.022

Stagnation Point Recession Correlation

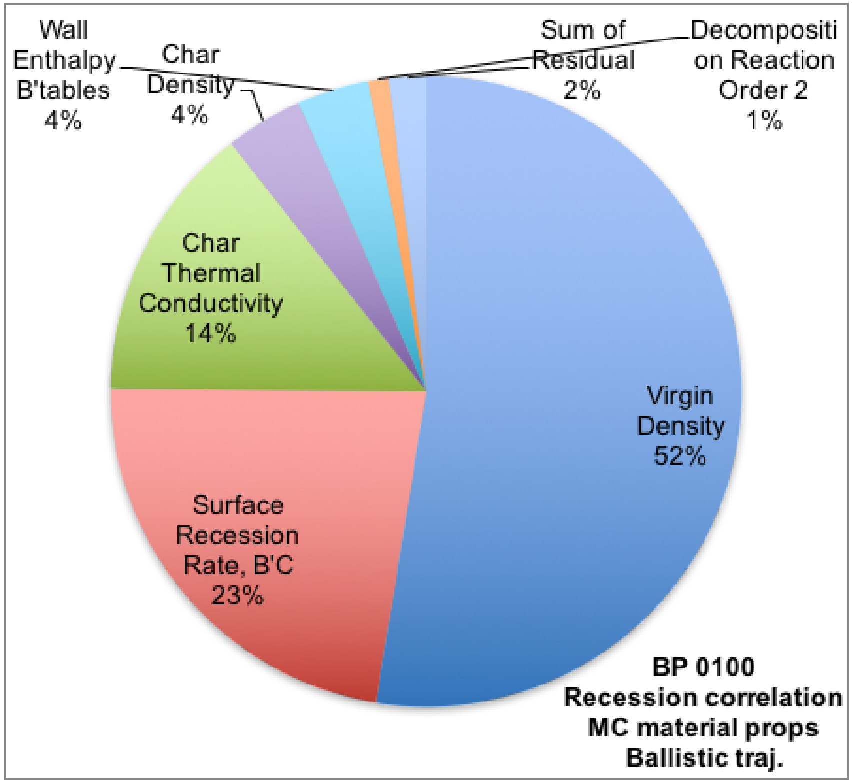
Orion TPS I/O

Guided



item	CorCoeff	CCsquared
Virgin Density	-0.754	0.568
Surface Recession Rate, B'C	0.396	0.157
Char Thermal Conductivity	-0.271	0.073
Char Density	0.242	0.058
Wall Enthalpy B'tables	-0.152	0.023
Decomposition Reaction Order 2	0.131	0.017

Ballistic



item	CorCoeff	CCsquared
Virgin Density	-0.722	0.521
Surface Recession Rate, B'C	0.473	0.224
Char Thermal Conductivity	-0.376	0.141
Char Density	0.199	0.039
Wall Enthalpy B'tables	-0.191	0.037
Decomposition Reaction Order 2	0.102	0.010

Summary of Results

Confidence Level 108°F (60°C) BTMM

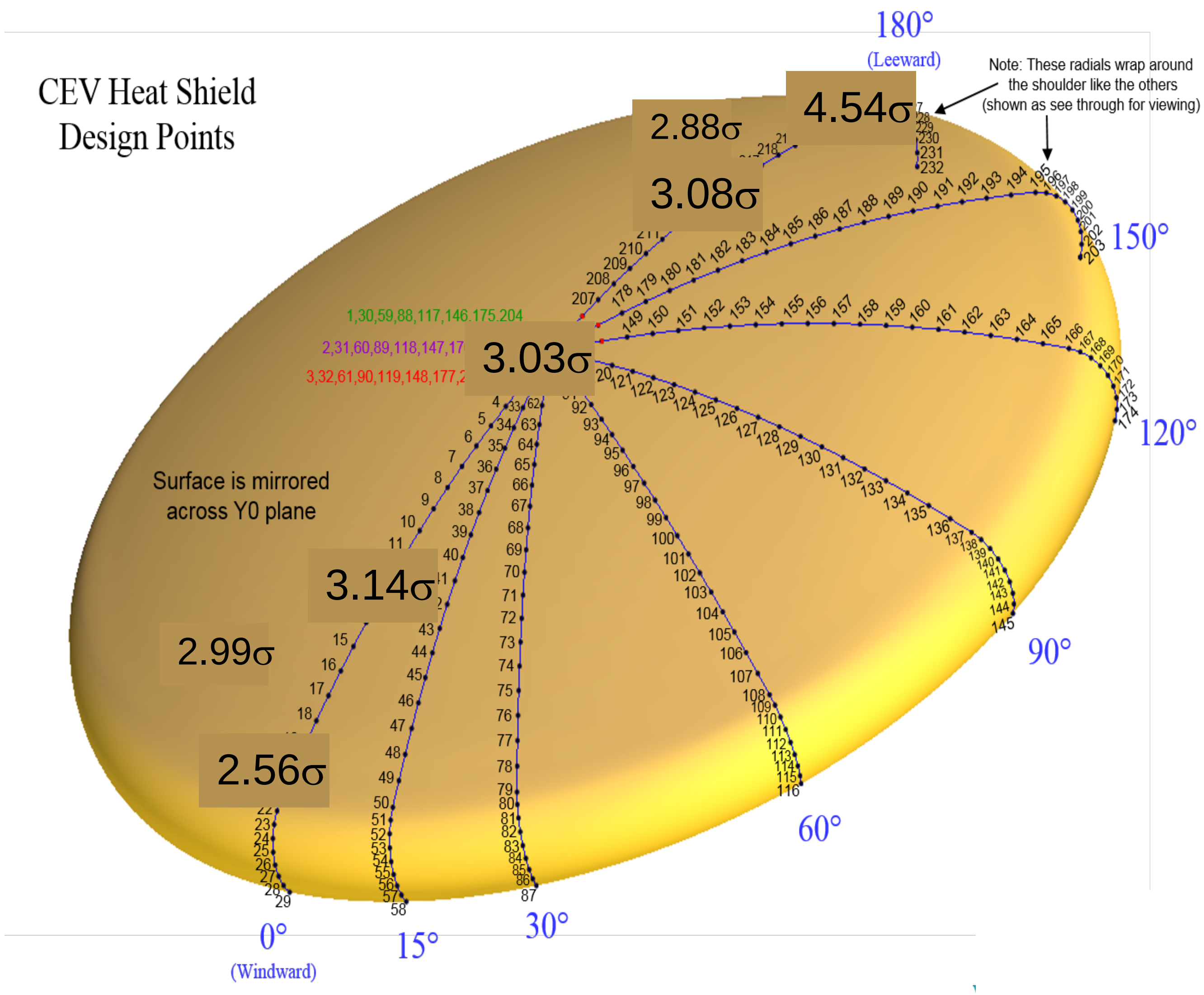
Orion TPS I/O

Guided Trajectory		
BP	SD mBLT, °C	60/SD
stagnation point	19.09	3.14
windside, acreage, off-centerline	20.07	2.99
acreage at windward shoulder, centerline	23.40	2.56
center of dish	19.78	3.03
leeward side, centerline, acreage	19.48	3.08
leeward side, acreage, off-centerline	20.81	2.88
leeward side, shoulder, centerline	13.22	4.54

Ballistic/Abort Trajectory		
BP	SD mBLT, °C	60/SD
stagnation point	17.67	3.40
windside, acreage, off-centerline	18.61	3.22
acreage at windward shoulder, centerline	22.80	2.63
center of dish	18.83	3.19
leeward side, centerline, acreage	27.30	2.20
leeward side, acreage, off-centerline	27.78	2.16
leeward side, shoulder, centerline	27.72	2.16

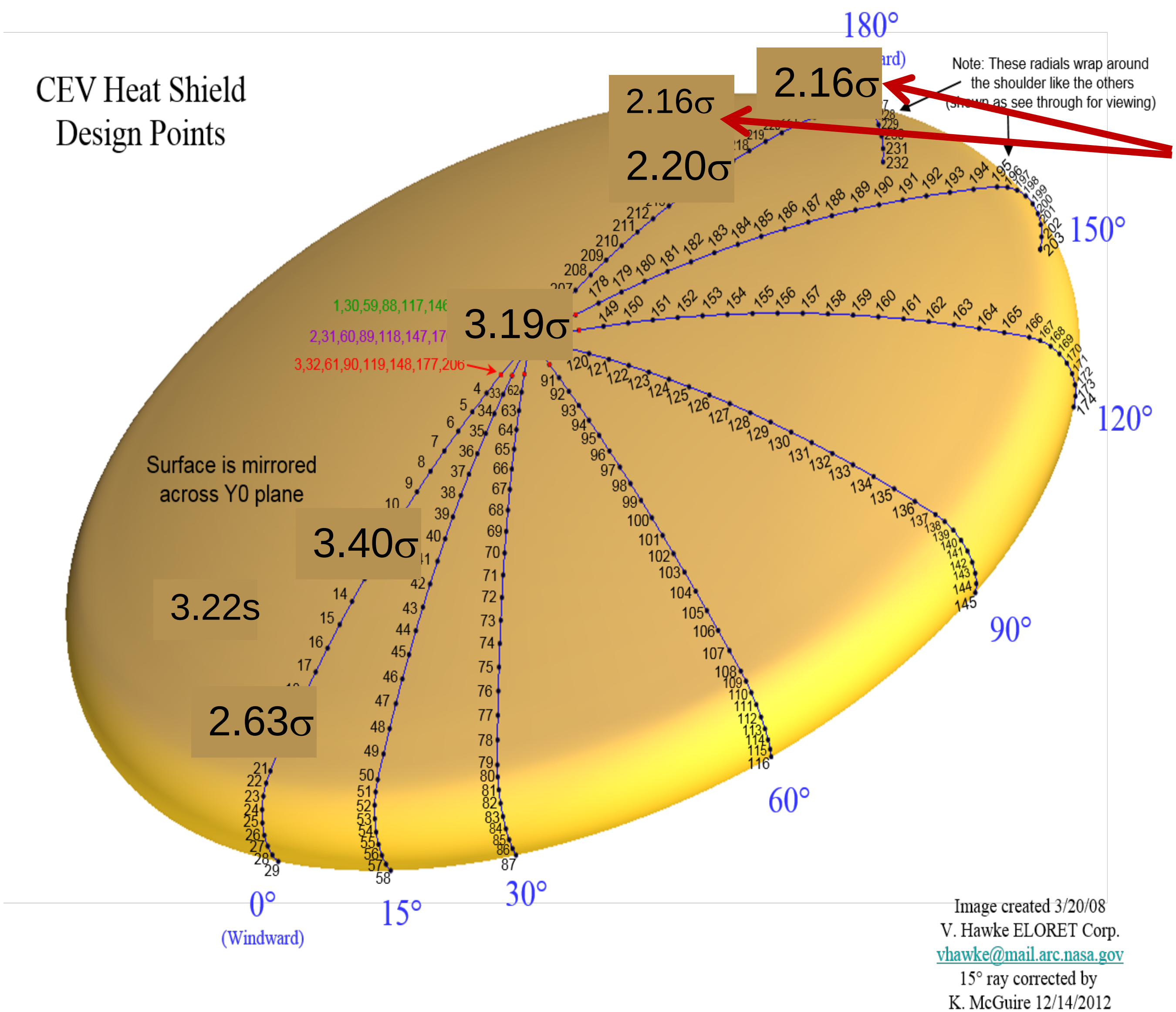
Guided Trajectory, Confidence

Orion TPS I/O



Ballistic Trajectory, Confidence

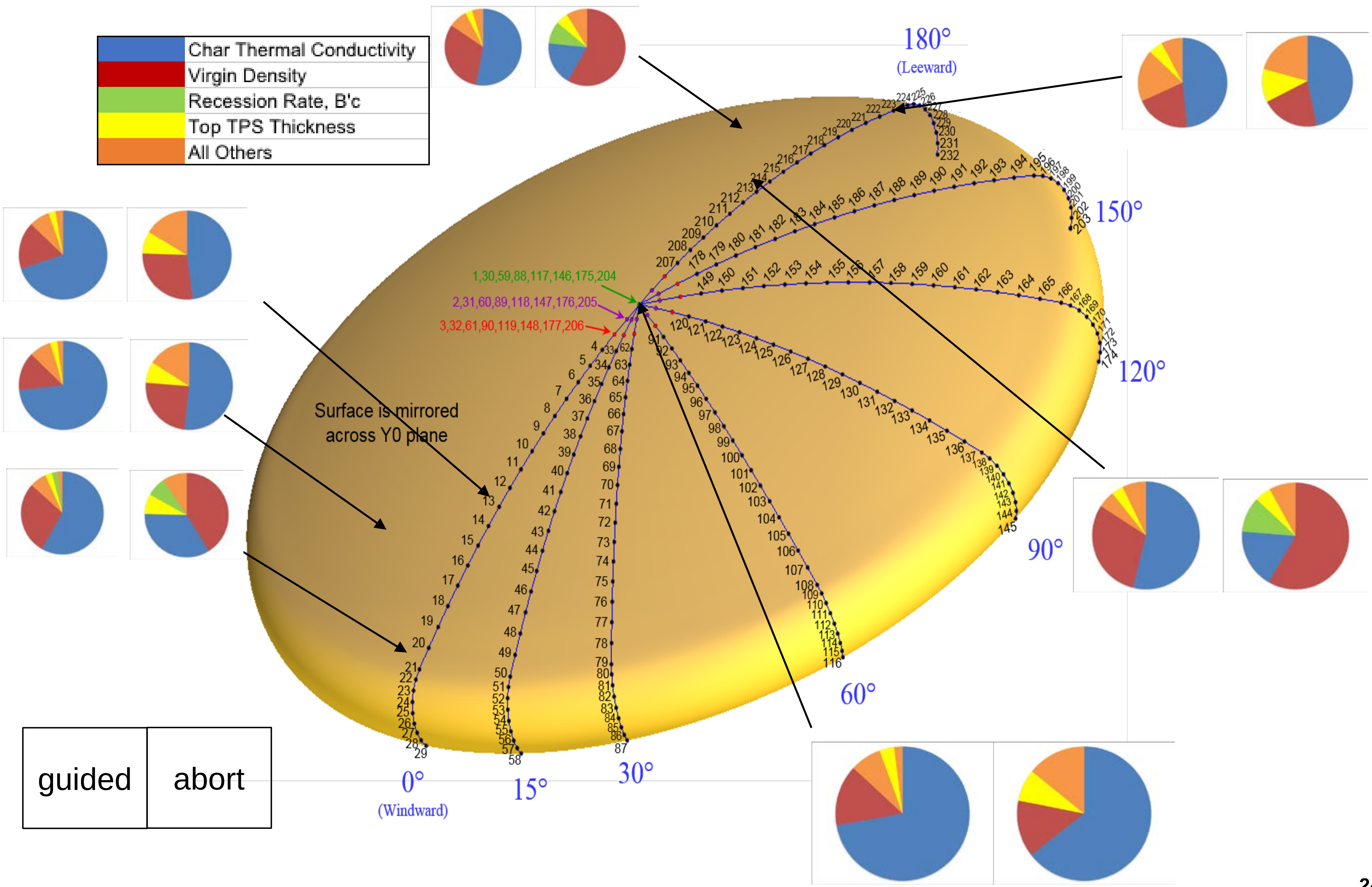
Orion TPS I/O



leeward points have the lowest confidence

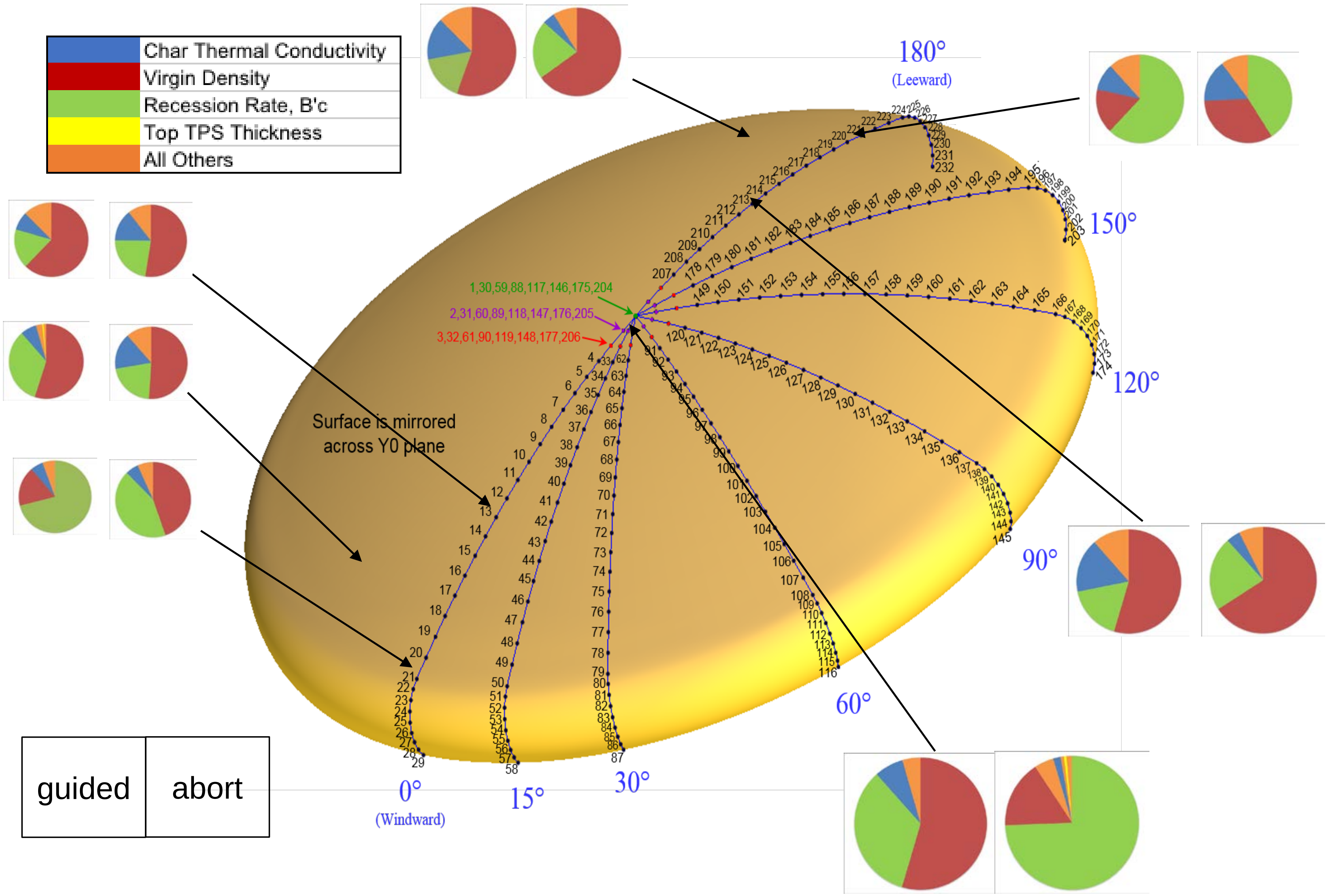
mBLT Correlations [Guided] [Abort] Trajectories

Orion TPS I/O



Recession Correlations [Guided] [Abort] Trajectories

Orion TPS I/O



Conclusion

Conclusion

Orion TPS I/O

1. The confidence interval for the 60°C BTMM has been determined at seven forebody bodypoint locations for the nominal guided and abort (ballistic) trajectories

2. Values range from 2.16σ to 4.54σ and are body point and trajectory specific

3. NASA is OK with these values

4. mBLT: Uncertainty in virgin density and char thermal conductivity account for 70 – 90% of the relative sensitivity in mBLT. Lowering the uncertainty in these parameters would be the easiest way to improve confidence intervals.

5. Recession: Uncertainty in B'c and virgin density account for 70 – 90% of the relative sensitivity in surface recession. Recall, the uncertainty in B'c is found from the uncertainty in Avcoat material composition.