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

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Order of Presentation

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

\[
\text{nominal TPS thickness} + \frac{1}{2} \left[ (\text{extra TPS} - \text{nominal TPS})^2 + \text{GNC uncertainty} + \text{aerodynamics uncertainty} + \text{material response uncertainty} \right]
\]
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.
• 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?
What is the confidence ($1\sigma$, $2\sigma$, 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

Uncertainties expressed as $2 \times \text{CoV}$ (standard deviation / mean) unless otherwise noted (pyrolysis gas enthalpy is scaled the same as char thermal conductivity).

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

### B'tables

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>B'c</td>
<td>0.15</td>
</tr>
<tr>
<td>Wall enthalpy</td>
<td>0.10</td>
</tr>
<tr>
<td>Density</td>
<td>0.04</td>
</tr>
<tr>
<td>Molecular weight</td>
<td>0.04</td>
</tr>
<tr>
<td>Roughness</td>
<td></td>
</tr>
<tr>
<td>Roughness height</td>
<td>0.487 not used</td>
</tr>
<tr>
<td>Height offset (constant)</td>
<td>-0.000223</td>
</tr>
</tbody>
</table>

### Substructure

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness, adhesive [m]</td>
<td>0.000254-0.000762 uniform</td>
</tr>
<tr>
<td>Thickness, composite</td>
<td>+/-0.000127 5 mil tolerance</td>
</tr>
<tr>
<td>Density</td>
<td>0.02</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>0.02</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.02</td>
</tr>
</tbody>
</table>

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

- Shoulder, centerline
- Stagnation point
- Center of dish
- Acreage, off-centerline
- Acreage, centerline
- Acreage/shoulder
How Are The Data Analyzed?

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

\[ 60^\circ C/SD(\circ C) = \text{Confidence Interval (}\sigma) \]
Example of the analysis – stagnation point

Note: These radials wrap around the shoulder like the others (shown as see through for viewing)

Surface is mirrored across Y0 plane
Stagnation Point mBLT Dispersion

Guided

BP 0100
MC matl props only
Guided traj
Avg. mBLT 254.7°C
SD = 19.09°C

Ballistic

BP 0100
MC matl props only
Ballistic traj
Avg. mBLT 251.2°C
SD = 17.67°C

mBLT = maximum bond line temperature
Stagnation Point Recession Dispersion

**Guided**

BP 0100
MC matl props only
Guided traj
Avg. recession = 0.0352 in.
SD = 0.0062 in.

**Ballistic**

BP 0100
MC matl props only
Ballistic traj
Avg. recession = 0.104 in.
SD = 0.0114 in.
Stagnation Point mBLT Correlation

Guided

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

Virgin Thermal Conductivity 70%
Char Thermal Conductivity 70%
Virgin Density 17%
Char Density 1%
Sum of Residual 1%
Initial TPS Thickness 3%
Top TPS Thickness 4%
Virgin Thermal Conductivity 4%
Initial TPS Temperature 4%

BP 0100 mBLT Correlation
MC mat prop only
Guided traj.

Ballistic

Char Density 3%
Virgin Thermal Conductivity 48%
Virgin Density 28%
Char Thermal Conductivity 8%
Top TPS Thickness 6%
Initial TPS Temperature 6%

BP 0100 mBLT Correlation
MC mat prop only
Ballistic traj.

<table>
<thead>
<tr>
<th>item</th>
<th>CorCoeff</th>
<th>CCsquared</th>
</tr>
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<tbody>
<tr>
<td>Char Thermal Conductivity</td>
<td>0.836</td>
<td>0.699</td>
</tr>
<tr>
<td>Virgin Density</td>
<td>-0.415</td>
<td>0.172</td>
</tr>
<tr>
<td>Initial TPS Temperature</td>
<td>0.197</td>
<td>0.039</td>
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<tr>
<td>Virgin Thermal Conductivity</td>
<td>0.191</td>
<td>0.036</td>
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<tr>
<td>Top TPS Thickness</td>
<td>-0.159</td>
<td>0.025</td>
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<tr>
<td>Char Density</td>
<td>0.113</td>
<td>0.013</td>
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</table>

<table>
<thead>
<tr>
<th>item</th>
<th>CorCoeff</th>
<th>CCsquared</th>
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</thead>
<tbody>
<tr>
<td>Char Thermal Conductivity</td>
<td>0.693</td>
<td>0.480</td>
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<tr>
<td>Virgin Density</td>
<td>-0.525</td>
<td>0.275</td>
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<tr>
<td>Top TPS Thickness</td>
<td>-0.284</td>
<td>0.081</td>
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<tr>
<td>Initial TPS Temperature</td>
<td>0.240</td>
<td>0.057</td>
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<td>Char Density</td>
<td>0.177</td>
<td>0.031</td>
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<tr>
<td>Virgin Thermal Conductivity</td>
<td>0.148</td>
<td>0.022</td>
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</table>
Stagnation Point Recession Correlation

Guided

- Char Thermal Conductivity 8%
- Surface Recession Rate, B'C 17%
- Char Density 6%
- Wall Enthalpy B'table 3%
- Decomposition Reaction Order 2 2%
- Sum of Residual 2%

Virgin Density 62%

Ballistic

- Virgin Density 52%
- Surface Recession Rate, B'C 23%
- Char Thermal Conductivity 14%
- Wall Enthalpy B'table 4%
- Char Density 4%
- Decomposition Reaction Order 2 1%
- Sum of Residual 2%

BP 0100 Recession correlation
MC material props
Guided traj.

BP 0100 Recession correlation
MC material props
Ballistic traj.

<table>
<thead>
<tr>
<th>item</th>
<th>CorCoef</th>
<th>CCsquared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin Density</td>
<td>-0.754</td>
<td>0.568</td>
</tr>
<tr>
<td>Surface Recession Rate, B'C</td>
<td>0.396</td>
<td>0.157</td>
</tr>
<tr>
<td>Char Thermal Conductivity</td>
<td>-0.271</td>
<td>0.073</td>
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<tr>
<td>Char Density</td>
<td>0.242</td>
<td>0.058</td>
</tr>
<tr>
<td>Wall Enthalpy B'table</td>
<td>-0.152</td>
<td>0.023</td>
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<tr>
<td>Decomposition Reaction Order 2</td>
<td>0.131</td>
<td>0.017</td>
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</table>

<table>
<thead>
<tr>
<th>item</th>
<th>CorCoef</th>
<th>CCsquared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin Density</td>
<td>-0.722</td>
<td>0.521</td>
</tr>
<tr>
<td>Surface Recession Rate, B'C</td>
<td>0.473</td>
<td>0.224</td>
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<tr>
<td>Char Thermal Conductivity</td>
<td>-0.376</td>
<td>0.141</td>
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<tr>
<td>Char Density</td>
<td>0.199</td>
<td>0.039</td>
</tr>
<tr>
<td>Wall Enthalpy B'table</td>
<td>-0.191</td>
<td>0.037</td>
</tr>
<tr>
<td>Decomposition Reaction Order 2</td>
<td>0.102</td>
<td>0.010</td>
</tr>
</tbody>
</table>
Summary of Results
# Confidence Level 108°F (60°C) BTMM

## Guided Trajectory

<table>
<thead>
<tr>
<th>BP</th>
<th>SD mBLT, °C</th>
<th>60/SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>stagnation point</td>
<td>19.09</td>
<td>3.14</td>
</tr>
<tr>
<td>windside, acreage, off-centerline</td>
<td>20.07</td>
<td>2.99</td>
</tr>
<tr>
<td>acreage at windward shoulder, centerline</td>
<td>23.40</td>
<td>2.56</td>
</tr>
<tr>
<td>center of dish</td>
<td>19.78</td>
<td>3.03</td>
</tr>
<tr>
<td>leeward side, centerline, acreage</td>
<td>19.48</td>
<td>3.08</td>
</tr>
<tr>
<td>leeward side, acreage, off-centerline</td>
<td>20.81</td>
<td>2.88</td>
</tr>
<tr>
<td>leeward side, shoulder, centerline</td>
<td>13.22</td>
<td>4.54</td>
</tr>
</tbody>
</table>

## Ballistic/Abort Trajectory

<table>
<thead>
<tr>
<th>BP</th>
<th>SD mBLT, °C</th>
<th>60/SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>stagnation point</td>
<td>17.67</td>
<td>3.40</td>
</tr>
<tr>
<td>windside, acreage, off-centerline</td>
<td>18.61</td>
<td>3.22</td>
</tr>
<tr>
<td>acreage at windward shoulder, centerline</td>
<td>22.80</td>
<td>2.63</td>
</tr>
<tr>
<td>center of dish</td>
<td>18.83</td>
<td>3.19</td>
</tr>
<tr>
<td>leeward side, centerline, acreage</td>
<td>27.30</td>
<td>2.20</td>
</tr>
<tr>
<td>leeward side, acreage, off-centerline</td>
<td>27.78</td>
<td>2.16</td>
</tr>
<tr>
<td>leeward side, shoulder, centerline</td>
<td>27.72</td>
<td>2.16</td>
</tr>
</tbody>
</table>
Guided Trajectory, Confidence

CEV Heat Shield Design Points

- 2.88σ
- 3.08σ
- 3.03σ
- 2.99σ
- 2.56σ

Surface is mirrored across Y0 plane

Note: These radials wrap around the shoulder like the others (shown as see through for viewing)
Ballistic Trajectory, Confidence

CEV Heat Shield Design Points

leeward points have the lowest confidence

Surface is mirrored across Y0 plane

Note: These radials wrap around the shoulder like the others (shown as seen through for viewing)

3.40σ
3.22s
2.63σ
3.19σ
2.20σ
2.16σ
2.16σ
mBLT Correlations
[Guided] [Abort] Trajectories
Conclusion
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 $2.16\sigma$ to $4.54\sigma$ 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.