Ablative Thermal Protection System (TPS) Margin Study

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An artist's rendering of the Apollo command module's re-entry into the Earth's atmosphere
Outline

• Objectives
• Possible Data Sources
• Trajectories
• Assumptions and Considerations
• Computational Tools and Techniques
• Ablation Overview
• Design of Experiments
• Reliability Assessment
• Conclusions
Objectives

1. Provide input to a planned arc jet testing campaign
   – Use Design of Experiments (DOE)

2. Assess the TPS reliability using the bondline temperature
   – Use Uncertainty Quantification (UQ)
   – Use Probabilistic Technology (PT)
   Temperature at the junction of ablative material to the carrier structure

3. Provide sensitivity inputs to the TPS margin and design process
   – Use UQ and PT
   – Not discussed in this presentation
Possible Data Sources

- Mission trajectory test flight(s)
  - Extremely limited and expensive
  - Continuously varying 3-D environmental conditions (from benign to ablative)
  - Mixture of laminar, transitional and turbulent flows

- Arc Jet experimental testing (NASA Ames and NASA Johnson)
  - Small sample size (30) testing of sample materials
  - Facility limitations
  - Axisymmetric approximation of discrete ablative conditions
  - Extended durations of laminar flow

- Mission trajectory computational simulations
  - Essentially infinite sample sizes
  - 1-D approximation of discrete or varying ablative behaviors
  - Usually modeled as fully turbulent flows (conservative assumption)
Trajectories

1. High heat flux
   – 2009–era focus mission
   – Most of existing data

2. **Intermediate heat flux**
   – 2011 primary mission
   – Limited existing data

3. **Low heat flux / high heat load**
   – 2011 secondary mission
   – Essentially no existing data

Focus for current work: DOE and Reliability Assessment
Assumptions and Considerations

• Use existing aerothermal test data and computational code
  – Large reproducibility uncertainty for existing test data
  – Key metric (bondline temperature) was not measured within the existing data
  – Few and highly uncertain test / computation comparisons
  – Model form correction term uncertainty

• Consider material property variations
  – 11 possible material variations within the computational code
  – Limited measured data available
  – No measured data for most of the possible material variations

• Reliability failure criterion
  – Not defined \textit{a priori}
  – Team defined “best guess” failure criterion as the work progressed
  – Consider a few failure criterion variants to determine the robustness of the reliability estimates
Computational Tools and Techniques

• STAB: aerothermal computational simulation code
• General statistical analysis (Microsoft Excel)
• DOE and UQ
  • Analysis of Variance (ANOVA) statistical technique
  • Design-Expert (DX8) software from Stat-Ease, Inc.
  • D-Optimal DOE proposed to maximize the information returned
• Uncertainty Propagation via probabilistic methods:
  • Monte Carlo Simulation (MCS) implemented by Green within UNIPASS software from PredictionProbe, Inc.
    – “Low” fidelity reliability assessment implementation
    – Baseline and alternative failure criteria (described subsequently)
  • First-Order Reliability Methods (FORM) implemented (under contract) within SPISE software from PredictionProbe, Inc.
    – “High” fidelity reliability assessment implementation
    – Alternative failure criteria (described subsequently)
Tests are typically conducted over durations of up to 300 seconds. The bondline temperature is currently used to establish the TPS reliability. However, bondline temperature was not measured, it is only simulated. There is considerable uncertainty in this aspect of the reliability assessment, as there were only 24 comparisons between test and computation available!
Ablation Overview

Simulated Thermocouple Response (STAB)

The bondline temperature increases well beyond test duration.

Maximum TC responses over time at each depth from STAB and Arc Jet Tests used to predict the maximum bondline temperature.

These TCs have “burned up” and no longer produce useful data.

Bondline temperature

Ablator Backwall
Ablation Overview
Heat Shield
Design Points and Integrated Heat Load Contours

Surface is mirrored across Y0 plane

Windward Side 0°

Leeward Side

180°

109

102

161

6

7

3

2

1

15

21

15°

30°

60°

90°

120°

150°

180°
Design of Experiments
Design Of Experiments (1)

Existing data is aligned with a high heat flux trajectory – not the primary current focus.
Design Of Experiments (3)

- Measured Arc Jet Data
- Project Proposed Test Plan
- Trajectory 1 Bounding Curve (fully margined)
- Trajectory 2 / BP 21 (fully margined)
- Trajectory 2 / BP 1 (fully margined)
- June 7B DOE Feedback: Okay
- June 7B DOE Feedback: Maybe
- June 7B DOE Feedback: No
- Trajectory 3 in lower left-hand corner
An objective comparison of 6 statistical metrics strongly favored the predictive capability of over Many fewer replicated points within than.
Reliability Assessment Process
Reliability Assessment
Problem Formulation

• The STAB computational model
• Presumed Safe Temp Limit
• Current heat shield design thickness and carrier structure
• Two trajectories analyzed (trajectories #2 and #3)
• Five heating environments, with various margining assumptions, were examined for each trajectory; these are bracketed by:
  – Case 0 = Transitional heating
  – Case 3 = Trajectory dispersion and aeroheating uncertainty (fully turbulent)
• Seven body points: one from each of the trajectory dispersion zones.
  – The body points are 1, 15, 21, 102, 109, 161, and 229.

70 Total Reliability Assessments:
2 trajectories X 5 environments X 7 body points
Reliability Assessment
Failure Criteria Formulation

- Baseline: system failure probability proportional to maximum multi-point exceedance of safe bondline temperature (UNIPASS)
- Alternative: joint multi-point probability of safe bondline temperature exceedance (UNIPASS and SPISE)

Failure data derived from limited materials testing; linear approximation used in this study to illustrate the idea.
Reliability Assessment
Response Surface Generation

During RS interrogation, the material property variations can be treated as correlated or not.

1000 case STAB run template of prescribed, random departures from nominal values for 11 material properties

Select reliability case (70 possible)

Bounded distribution; easy to implement

\[ \text{Btemp} = \text{Beta}(\text{MV}, \text{SD}, \text{XL}, \text{XU}) \]
\[ \text{MV} = \text{mean value}; \text{SD} = \text{stdev} \]
\[ \text{XL} = \text{lo bound}; \text{XU} = \text{hi bound} \]
or,
\[ \text{Btemp} = \text{Uniform}[\text{XL}, \text{XU}] \]

lumped material properties

Implemented in UNIPASS by Green using MCS

\[ \text{Btemp} = f(\text{X1}, \text{X2}, \ldots \text{X11}) \]

11-dimensional cubic RS

distinct material properties

Implemented in SPISE by PPI using FORM

During RS interrogation, the material property variations can be treated as correlated or not.
Reliability Assessment

Reliability Assessment Process

3 Nested loops:

1. Outermost loop: problem setup
   - Select “safe” bond line temperature
   - Select the exact form of the reliability formulation:
     - Material property variation RS form
     - Failure constraint
     - Number of MCS samples
     - Confidence level, convergence tolerances, etc.

2. Intermediate loop: select user input value of $T_{Hi}$
   - Upper bound of model form correction uncertainty term
   - Treat this term as a uniform distribution $[T_{Lo}, T_{Hi}]$

3. Innermost loop: conduct reliability assessment subject to material property variations (11-D cubic, or 1-D Beta / Uniform RS) with
   - Added model form correction uncertainty term from loop 2
   - Failure constraint associated with “safe” temperature from loop 1
Reliability Assessment Results
Reliability Assessment
Trajectory 3, Case 0

System Reliability %

Higher Reliability

Lower Reliability

Less Model Form Uncertainty

More Model Form Uncertainty

$T_{Hi}$, Unc Limit, deg F
Reliability Assessment
Trajectory 2 and 3, Case 0

Lower reliability for same amount of model form uncertainty

Greater tolerance for model form uncertainty at same reliability level

Traj 2 has greater reliability than does Traj 3 under similar assumptions
Reliability Assessment
Trajectory 2 and 3, Case 0 and 3

Coincidental alignment of Traj 2, Case 3 With Traj 3, Case 0

System Reliability % vs. $T_{Hi}$, Unc Limit, deg F
Reliability Assessment
Trajectory 3, Case 0, Different Failure Modes

Proposed risk-based failure mode:
\[ L \times C \]
\[ \text{Prob(Temp)} \times \text{Prob(Fail}_{\text{SYS}}(\text{Temp})) \]

Baseline Failure Mode
(Consequence, C)

Alternative Failure Mode
(Likelihood, L)

Not Implemented
Reliability Assessment

Trajectory 3, Case 0, Effect of CDF Confidence Level, Baseline Failure Mode

![Graph showing the effect of CDF confidence level on system reliability as a function of temperature. The graph plots system reliability (%) against temperature ($T_{Hi}$, Unc Limit, deg F) for different confidence levels (90%, 95%, 99%, 99.9%) with distinct markers and line styles. The graph indicates a decreasing trend in system reliability with increasing temperature.]
Reliability Assessment
Trajectory 3, Case 0, Effect of Material Property Variations, Correlation and Beta/Uniform Modeling

![Graph showing the relationship between System Reliability % and T_{Hi}, Unc Limit, deg F.](image)
Summary

• D-Optimal Design of Experiments for new arc jet testing campaign

• Reliability Assessment Formulation
  – Baseline:
    • Model Form Uncertainty (Test – Computation) = Function of $T_{Hi}$
    • Two trajectories
    • Five heating environments
    • Seven body points
  – Variants:
    • Material property variation RS options (11-D cubic, 1-D Beta or Uniform distributions)
    • Probabilistic method (Monte Carlo Simulation or FORM)
    • Baseline or alternative failure criteria
    • Analysis platform (UNIPASS or SPISE)
    • Confidence level and body point correlation
Study Closeout

• Key findings:
  – Three sources of uncertainty within the system wide analysis were found to have a dominant effect on the reliability assessment
  – Different forms of the reliability assessment formulation yielded very different reliability assessment results
  – The DOE process for test planning resulted in a technically improved test matrix for the thermal response tests
The End

Thank You!
Back
Up
Charts
Two modes of operation:
1. Simulated arc jet testing (fixed environmental conditions for a given duration)
2. Simulated mission trajectory for a given body point (variable environmental conditions)
Design of Experiments (5)

Design-Expert® Software
Factor Coding: Actual
Recession

Design Points
0.763
0.07

X1 = A: P
X2 = B: Qcw

Original Data (1)

Original data + Program Proposal (2)

Average metrics over 10 samples
Highlights show the better of the two metrics
Rec = Rec(P, Qcw);
Dur dependence ignored here for the sake of illustration

<table>
<thead>
<tr>
<th>Metric</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>StDev</td>
<td>0.0716</td>
<td>0.0515</td>
<td>0.0597</td>
</tr>
<tr>
<td>PRESS</td>
<td>0.2574</td>
<td>8.7359</td>
<td>3.7370</td>
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<tr>
<td>R-Sq</td>
<td>0.8980</td>
<td>0.9802</td>
<td>0.9832</td>
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<tr>
<td>Adj R-Sq</td>
<td>0.8788</td>
<td>0.9635</td>
<td>0.9699</td>
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<tr>
<td>Pred R-Sq</td>
<td>0.8397</td>
<td>-0.8969</td>
<td>0.5404</td>
</tr>
<tr>
<td>Adeq Prec</td>
<td>19.9239</td>
<td>42.9057</td>
<td>51.6837</td>
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</tbody>
</table>

Original data + Green Proposal (3)

Design-Expert® Software
Factor Coding: Actual
Recession

Design Points
1.16814
-0.297814

Design-Expert® Software
Factor Coding: Actual
Recession

Design Points
1.01411
-0.48204

X1 = A: P
X2 = B: Qcw

Original data + Program Proposal (2)

Original data + Green Proposal (3)
# Reliability Assessment

## Reliability Cases

<table>
<thead>
<tr>
<th>Margining Process Case Identifier</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No trajectory dispersion, no aerothermal margin, transitional heating</td>
</tr>
<tr>
<td>1</td>
<td>No trajectory dispersion, no aerothermal margin, fully turbulent</td>
</tr>
<tr>
<td>2</td>
<td>No trajectory dispersion, aerothermal uncertainty, fully turbulent</td>
</tr>
<tr>
<td>3</td>
<td>Trajectory dispersion, aerothermal uncertainty, fully turbulent</td>
</tr>
<tr>
<td>4</td>
<td>Trajectory dispersion, no aerothermal uncertainty, fully turbulent</td>
</tr>
</tbody>
</table>

“Best Estimate” Trajectory

Bracket the results

“Fully Margined” Trajectory
This briefing is for status only and does not represent complete engineering data analysis.

Computation of Bond line Temperature ($B_{\text{Temp}}$) under material property variations.

- $T_{\text{Rise}}$ predicted by STAB RS (Beta dist)
- $T_{\text{Corr}}$ selected from test correlation, bounded by $T_{\text{Hi}}$ (Uniform Dist)

Reliability Assessment Process Illustration:

- Ambient Temperature
- 10,000 to 1,000,000 samples to establish reliability estimate
- Assumed $T_{\text{Safe}}$

Max Unc Increment $T_{\text{Hi}}$

Failure Domain