Mars Science Laboratory Heatshield Flight Data and Analysis

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Outline

• MSL Entry Descent and Landing Overview
• Heatshield Instrumentation (MEDLI)
• Heatshield Flight Data
• Turbulent Transition
• Comparison to Model Predictions
• Surface Heating Reconstruction
• Mars2020 Heatshield Instrumentation (MEDLI2)
Mars Science Laboratory Entry Vehicle

- Successfully landed the Curiosity rover on the Martian surface on August 5th, 2012
- The entry vehicle was a 70-degree 4.5-m diameter spherocone
  - First lifting entry at Mars, nominal hypersonic angle of attack of 16 degrees
- The forebody heatshield was made of Phenolic Impregnated Carbon Ablator (PICA) tiles
  - Same material was used on NASA Stardust mission and SpaceX Dragon
- Backshell was shielded using SLA-561V and Acusil-II

MSL Entry Descent and Landing Sequence
  (Steltzner et al., JSR, 2014)
- Observed failures in shear testing of SLA-561V led to a late switch of TPS material to PICA
  - Heatshield thickness was set to 1.25” based on max allowable mass
  - Design focused on showing that PICA can survive heating environments and as-built thickness was sufficient

- Significant effort was made to model aerothermal environments and validate CFD tools using ground experimental data
  - AEDC Tunnel 9, Langley 20 in. Mach 6, CalTech T5, CUBRC LENS I
  - Generally good agreement between model predictions and ground data
  - Ground data showed higher heating in stagnation region

- Design environments used conservative assumptions
  - Fully turbulent, supercatalytic (full recombination to freestream composition)
  - Include heating augmentation due to distributed roughness
  - Include margins to account for biases/uncertainties
MSL Heatshield Design (2)

- MSL heatshield was made of PICA tiles with RTV gap fillers
- Orion TPS Advanced Development Project and MSL program conducted many arcjet tests to qualify PICA and gap filler design and to develop PICA response model
- Observed RTV fencing at low heating conditions
  - Dependent on heat flux, exposure time and gap filler direction with respect to flow
- Observed augmented PICA recession in ground shear tests
  - Compared to recession predicted by equilibrium gas-surface chemistry models
  - Led to inclusion of a recession lien in heatshield sizing
  - Later suspected to be due to test coupon design

Augmented PICA Recession in Shear Testing

Stagnation and Shear Testing of RTV Gap Fillers

Ref: AIAA 2009-4229
Heatshield Instrumentation

• The MSL Entry, Descent and Landing (EDL) Instrumentation Suite (MEDLI), located on the heatshield:
  - MEADS (Mars Entry Atmospheric Data System), Pressure ports and transducers
  - MISP (MEDLI Integrated Sensor Plug), In-depth temperature and isotherm sensors embedded in the PICA Thermal Protection System (TPS)

• MEDLI represents the most heatshield instrumentation flown on a Mars mission to date
MEDLI Integrated Sensor Plug (MISP)

- Seven MISP plugs installed at different locations on the heatshield covering a wide range of heating environments
- Each MISP is a 1.3” in diameter by 1.14” long PICA plug, inserted in heatshield and bonded on the sides and bottom with RTV-560
- Each MISP plug contains four type-K thermocouples (TC1-4) and one isotherm sensor (HEAT), sampled at 8, 2, or 1 Hz depending on location
  - In Plugs 5 and 7, only the top two thermocouples were operational due to data channel limitations
- Only the TC data are discussed here (HEAT sensor returned noisy data due to a data system issue)
MISP Flight Thermocouple Data

- All thermocouples returned data successfully
- All near surface thermocouples survived the heat pulse → TPS recession < 0.1 inch
- Boundary layer transition observed as sudden temperature slope changes
Boundary Layer Transition

• MSL studies used a momentum thickness Reynolds number (Re_θ) threshold to determine that heatshield will likely experience turbulent heating
  - Ground test data suggested transition for Re_θ > 200

• This led to design to fully turbulent environments at all locations on the heatshield

• Transition time can be inferred from the temperature derivative of shallowest TC

• Boundary layer Reynolds numbers can be calculated using CFD tools on the best estimated trajectory (BET)

• No single value of Re_θ explains transition front speed between MISP3 & MISP7

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<table>
<thead>
<tr>
<th>Plug</th>
<th>Inferred transition Time</th>
<th>Predicted Transition Time with Re_θ &gt; 200</th>
<th>Calculated Re_θ at inferred transition time</th>
</tr>
</thead>
<tbody>
<tr>
<td>MISP3</td>
<td>63 seconds</td>
<td>52 seconds</td>
<td>394</td>
</tr>
<tr>
<td>MISP2</td>
<td>64 seconds</td>
<td>52 seconds</td>
<td>405</td>
</tr>
<tr>
<td>MISP6</td>
<td>65 seconds</td>
<td>57 seconds</td>
<td>293</td>
</tr>
<tr>
<td>MISP7</td>
<td>65 seconds</td>
<td>70 seconds</td>
<td>158</td>
</tr>
<tr>
<td>MISP5</td>
<td>73 No transition</td>
<td></td>
<td>125</td>
</tr>
</tbody>
</table>
Turbulent Transition Due to Roughness

- Transition criterion:
  - Transition may also be induced by roughness, described by a Roughness Reynolds ($Re_{kk}$) number based on roughness height ($k$)
  - Ballistic range studies have shown that CO$_2$ flows trip at lower $Re_{kk}$ numbers than in air, for both discrete and distributed roughness
    - Transition threshold for distributed roughness in CO$_2$: $Re_{kk} > 223 \pm 55$ [Wilder, AIAA 2015-1738]
  - Two possible sources of distributed roughness considered for MEDLI: Roughness of PICA & Series of trips from RTV swelling

- Distributed roughness: PICA
  - Distributed roughness at design conditions is small (<0.6mm at most)
  - Transition not well predicted based on such low roughness heights

- Series of trips: RTV gap fillers swelling
  - Flow passed over a series of tile gaps and upstream MISP fences
  - RTV fences creates roughness elements as high as 2 mm acting like distributed roughness
  - $Re_{kk}$ at flight transition times (for $k = 2$ mm) agrees with threshold derived from ballistic range testing
  - However, MISP5 transition still not well predicted (closest to stag point and least affected by upstream trips)

<table>
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<tr>
<th>Plug</th>
<th>Inferred Transition Time (seconds)</th>
<th>$Re_{kk}$ at inferred transition time ($k = 2$ mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MISP3</td>
<td>63</td>
<td>198</td>
</tr>
<tr>
<td>MISP2</td>
<td>64</td>
<td>219</td>
</tr>
<tr>
<td>MISP6</td>
<td>65</td>
<td>230</td>
</tr>
<tr>
<td>MISP7</td>
<td>65</td>
<td>211</td>
</tr>
<tr>
<td>MISP5</td>
<td>73</td>
<td>525</td>
</tr>
</tbody>
</table>
Model Predictions of In-depth Temperature

- Surface heating is calculated using CFD code DPLR based on best-estimate trajectory
  - Best-estimate environments don’t use conservative assumptions made for design environments
  - Mitcheltree and Gnoﬀo 8-species 12-reactions Mars thermochemical non-equilibrium model
  - Mitcheltree surface catalycity model
  - Turbulent flow is modeled with Baldwin-Lomax algebraic model
  - Surface assumed to be in radiative equilibrium
  - Transition time is inferred from flight data
  - Consistent with design, shock layer radiation is assumed to be negligible

- Material response calculations are performed using Fully Implicit Ablation and Thermal (FIAT) response program
  - Equilibrium gas-surface chemistry is used to solve a surface energy balance that determines recession and conduction into material
  - Analysis is done with and without recession

\[ C_H(H_r - h_w) + \dot{m}_g h_g + \dot{m}_c h_c - (\dot{m}_c + \dot{m}_g) h_w + \alpha_w q_{rad} - \sigma \epsilon_w (T^4_w - T^4_\infty) - q_{cond} = 0 \]
Comparison of TC Data with Predictions

- TC burnout predicted at four MISP plugs with nominal recession model
  - Equilibrium models known to over predict recession at low conditions
  - Leads to inaccurate prediction of in-depth temperatures
Comparison with Predictions (No Recession)

Under prediction of windside laminar heating potentially due to radiation

Turbulent leeside peak temperature matches flight data

Under prediction of apex heating potentially due to turbulent overshoot or gap filler effects

Slower temperature drop in flight data compared to predictions potentially due to radiation or chemistry model deficiency

Under prediction of windside laminar heating potentially due to radiation
Surface Heating Reconstruction

- Inverse methods can be used to reconstruct surface heating from in-depth temperature data
  - The surface heating is estimated by minimizing the difference between temperature predictions and TC flight data (iterative process)
  - Gauss-Newton method for minimization
  - Tikhonov first-order regularization to alleviate oscillations

- Two estimation approaches were pursued:
  1. Estimate surface film coefficient, \( C_H \), using a detailed energy balance equation and equilibrium chemistry model for TPS material

\[
C_H(H_r - h_w) + \dot{m}_g h_g + \dot{m}_c h_c - (\dot{m}_c + \dot{m}_g) h_w + \alpha_w q_{rad} - \sigma \epsilon_w (T_w^4 - T_\infty^4) - q_{cond} = 0
\]

  2. Estimate heat rate using a simplified energy balance equation assuming no surface recession

\[
q_s + \alpha_w q_{rad} - \sigma \epsilon_w (T_w^4 - T_\infty^4) - q_{cond} = 0
\]

- Nom. Surface Heating
- Nom. Material Model
- Flight Temp. Data
- FIAT
- In-depth Temperature
- Updated Surface Heating
- Inverse Method
Challenges with $C_H$ Estimation

• The PICA equilibrium chemistry model is known to be inaccurate for MSL low heating conditions and tends to overestimate surface recession
  - Flight data suggest that recession was less than 0.1” (TC1 depth) at all plugs
  - PICA equilibrium model predicts recession advancing deeper than TC1 depth

• Inaccuracy of the equilibrium model also results in an inaccurate estimation of wall enthalpy
  - Wall and edge enthalpy approach one another at ~85 s
  - The convective term approaches zero and the in-depth thermal response loses sensitivity to $C_H$

• There is no validated finite-rate gas-surface chemistry model for PICA in CO$_2$ yet

\[
C_H(H_r - h_w) + \dot{m}_g h_g + \dot{m}_c h_c - (\dot{m}_c + \dot{m}_g) h_w + \alpha_w q_{rad} - \sigma \varepsilon_w (T_w^4 - T_\infty^4) - q_{cond} = 0
\]
Heat Rate Estimation Assuming No Recession

- A more simplified energy balance equation is also implemented in FIAT which does not require the PICA ablation model
  - Allows reconstruction of net heat rate (not directly comparable with CFD convective heat flux)
  - Assumes zero surface recession

\[ q_s + \alpha_w q_{rad} - \sigma \epsilon_w (T_w^4 - T_\infty^4) - q_{cond} = 0 \]

- MISP5 experienced the highest heating before transition (consistent with laminar predictions)
- MISP7 experienced higher turbulent heating than predictions
- Performed recession sensitivity and Monte Carlo analysis to assess reconstruction uncertainty (Mahzari et al., JSR 2015)
Follow-on Studies: Shock Layer Radiation

- Radiative heating was thought to be negligible during design
  - Simulations predicted < 1W/cm²

- Missing mechanism: high CO₂ density at moderately high temperatures (3000-4000 K) leads to radiation from CO₂ vibrational modes
  - Peaks later in trajectory

- Cruden et al. performed shock tube tests and simulations to characterize MSL’s radiative heating
  - Significant mid-infrared radiation resulting in additional heat flux as high as 15 W/cm²

- Including radiation in predicted heating improves the match with heating inferred from flight in stagnation region, but doesn’t explain all the discrepancy
  - Remaining discrepancy most likely due to deficiency of equilibrium gas-surface chemistry model

In a recent study, Oliver employed a decoupled technique to reconstruct surface heating with kinetically limited recession models. This technique allows for $C_H$ reconstruction without being limited by the equilibrium model. More straightforward to compare $C_H$ with CFD predictions. Performed sensitivity studies by varying different model inputs and identified feasible solutions based on flight’s upper bound on recession.

Summary of Findings from MISP Data

• Aeroheating
  - MSL designed to fully turbulent; flight data clearly shows turbulent transition and heating
  - Front progression is consistent with roughness-induced transition due to RTV swelling
  - Heating near stagnation region is underpredicted (partially explained by radiation)
  - Heating near apex region is underpredicted by smooth-wall CFD; higher heating may have been caused by RTV protuberance, currently being investigated
  - Heating predictions in the leeside flank region agree well with flight heating (under assumption of negligible recession)

• Material Response
  - Overprediction of PICA recession by equilibrium models at MSL conditions
  - No evidence of augmented recession in shear conditions
  - Underprediction of TC temperatures during cool-down is possibly due to deficiency of equilibrium recession model
  - The in-depth response model performs reasonably well in predicting temperatures
  - Early rise and plateau behavior that is often observed in arcjet TC data at low temperatures also occurred in flight
MEDLI2

- Mars2020 mission will use the same entry vehicle design as MSL and will be instrumented with MEDLI2 sensors
- MISP sensors
  - 11 plugs in PICA heatshield containing 17 TCs (better mapping of transition front compared to MEDLI)
  - 6 plugs in SLA-561V backshell containing 7 TCs
  - 3 heat flux sensors in the backshell (2 total flux, 1 radiative)
- MEADS sensors
  - 1 hypersonic and 6 supersonic pressure transducers in the heatshield
  - 1 pressure transducer on the backshell
- Post-flight analysis will incorporate improved models and lessons learned from MEDLI
Further Reading

Questions?
Backup
HEAT Sensor Data

Transient Data Noisy

Steady State Data Being Evaluated

MISP 3
MISP 2
MISP 6
MISP 7
MISP 5
MISP 1
MISP 4

MISP4 HEAT sensor not wired
MISP Plugs Against Tile Layout

- Flow may cross many gap fillers and other plugs before reaching a MISP plug.
• Employ a decoupled approach to investigate the effect of recession on heating estimates

• Reconstruction of heat rate profile from in-depth temperature measurements yields a unique solution for the temperature field in the ablator (regardless of surface location)

• After reconstruction, net heat rate can be calculated for any given surface location at any given time

• Definition of a recession profile will yield a surface heating profile

• In the absence of any recession data, we defined the recession profile based on the scaling of the nominal FIAT equilibrium model predictions
Monte Carlo simulation performed around the inverse estimation routine to quantify uncertainty bounds with heat rate estimates

- Gaussian distributions for eight input parameters based on material property testing and engineering judgment
- The MC simulation does not include recession uncertainty

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Std. Dev. (% of nominal)</th>
<th>Parameter</th>
<th>Std. Dev. (% of nominal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_v$</td>
<td>0.75%</td>
<td>Char yield</td>
<td>1% (corr.)</td>
</tr>
<tr>
<td>$C_{p_v}$</td>
<td>4%</td>
<td>$C_p$</td>
<td>1%</td>
</tr>
<tr>
<td>$\kappa_v$</td>
<td>7.5%</td>
<td>$\kappa_e$</td>
<td>10% (corr.)</td>
</tr>
<tr>
<td>$\epsilon_{v,c}$</td>
<td>1.5%</td>
<td>TC1 depth error</td>
<td>0.0015 inch</td>
</tr>
</tbody>
</table>
Anchoring ablator simulations with TC data

- A direct method of analyzing TPS response is to solve only in-depth heat conduction model
  - Perform this analysis with the FIAT (Fully Implicit Ablation and Temperature) 1-D model, using the PICA model
  - Use flight TC data as a temperature boundary condition to anchor the solution, so-called “TC driver” method
  - Every TC is a potential boundary condition, so several TC drivers are possible for each MISP

- We find that our ability to predict a TC response improves the closer the anchoring TC becomes
- Some phenomena are not well-predicted by the model, including the “hump” observed in the two deepest TCs at all MISP
- We can predict the response of deeper TCs well within ± 50 K in all plugs