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 spherecone
  - 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)
MSL Heatshield Design (1)

- 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
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 ($Re_\theta$) threshold to determine that heatshield will likely experience turbulent heating
  - Ground test data suggested transition for $Re_\theta > 200$
- 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 $Re_\theta$ explains transition front speed between MISP3 & MISP7

### Time derivatives of TC1

![Time derivatives of TC1](image)

<table>
<thead>
<tr>
<th>Plug</th>
<th>Inferred transition Time</th>
<th>Predicted Transition Time with $Re_\theta &gt; 200$</th>
<th>Calculated $Re_\theta$ 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 seconds</td>
<td>No transition</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 create 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 stagg 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 Gnofo 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

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

- Turbulent leeside peak temperature matches flight data.
- Slower temperature drop in flight data compared to predictions potentially due to radiation or chemistry model deficiency.
- Under prediction of apex heating potentially due to turbulent overshoot or gap filler effects.
- 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
     \[
     C_H (H_T - h_w) + \dot{m}_g h_g + \dot{m}_c h_c - (\dot{m}_c + \dot{m}_g) h_w + \alpha_w q_{rad} - \sigma \varepsilon_w (T_w^4 - T_{\infty}^4) - q_{cond} = 0
     \]
  2. Estimate heat rate using a simplified energy balance equation assuming no surface recession
     \[
     q_s + \alpha_w q_{rad} - \sigma \varepsilon_w (T_w^4 - T_{\infty}^4) - q_{cond} = 0
     \]
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

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

**Predicted Edge and Wall Enthalpy at MISP 2**

**$C_H$ Estimation at MISP2**
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

Follow-on Studies: Recession 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
MISP Plugs Against Tile Layout

- Flow may cross many gap fillers and other plugs before reaching a MISP plug.
Sensitivity to Recession Uncertainty

- 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.
Heat Rate Reconstruction Uncertainty

- 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>$C_p_e$</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>$\varepsilon_{v,c}$</td>
<td>1.5%</td>
<td>TC1 depth error</td>
<td>0.0015 inch</td>
</tr>
</tbody>
</table>

MISP2
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