Estimation of Heatshield Mass Loss for Mars2020 Entry Vehicle

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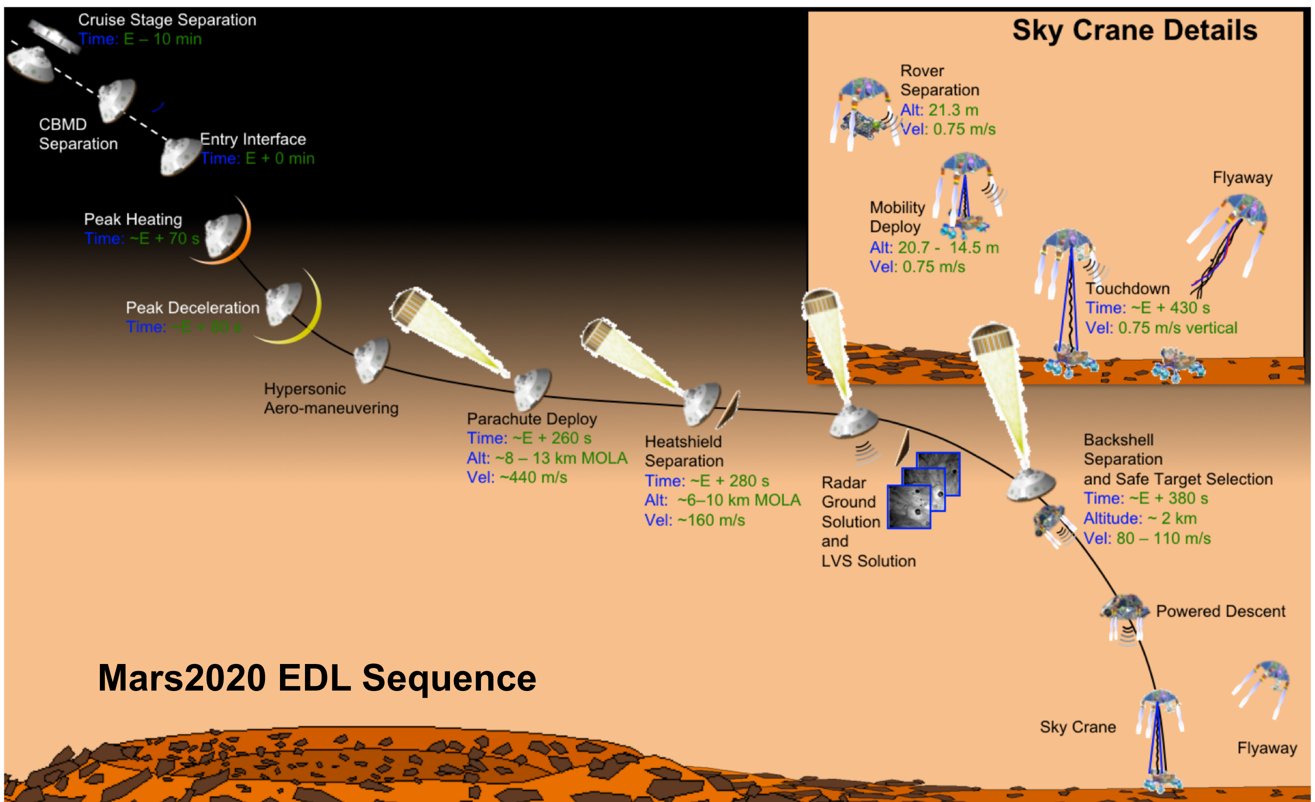
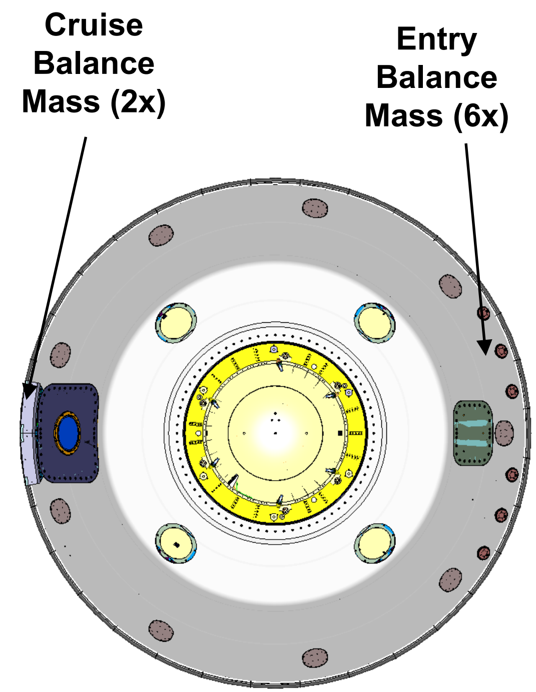
Outline

- Mars2020 entry vehicle and heatshield
- Motivation for estimating heatshield mass loss
- MSL approach for estimating heatshield mass loss
- Higher-fidelity approach for Mars2020
  - Analysis process and assumptions
  - Mass loss results
  - Comparison of temperature response to MSL Flight Data
- Application of mass loss analysis results in entry vehicle design

Mars2020/MSL Entry Vehicle

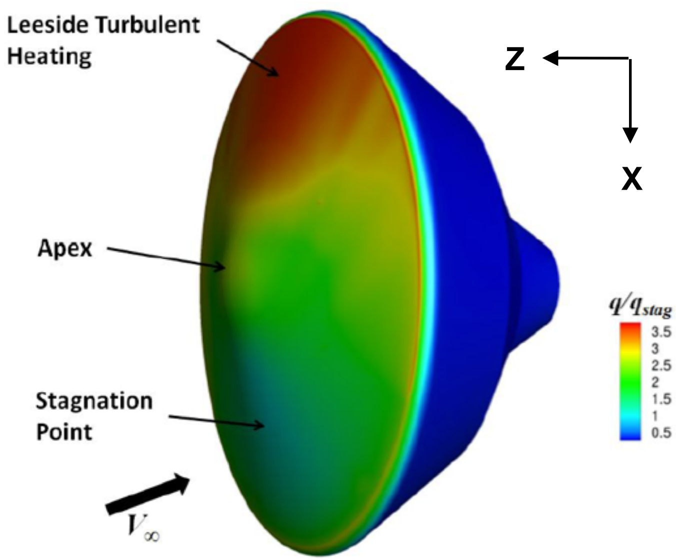
- Mars2020 EDL sequence and entry vehicle design is very similar to MSL
  - Build-to-print with minor changes in vehicle design and descent sequence
  - Cruise Balance Mass (CBM) jettisoned prior to entry to offset CG such that the vehicle flies at a trim angle of attack hypersonically and generates lift for hypersonic guidance
  - Entry Balance Mass (EBM) jettisoned prior to parachute deploy to return vehicle's CG to its axis of symmetry to be aligned with parachute deployment direction
  - Heatshield ablates and loses mass during the heat pulse



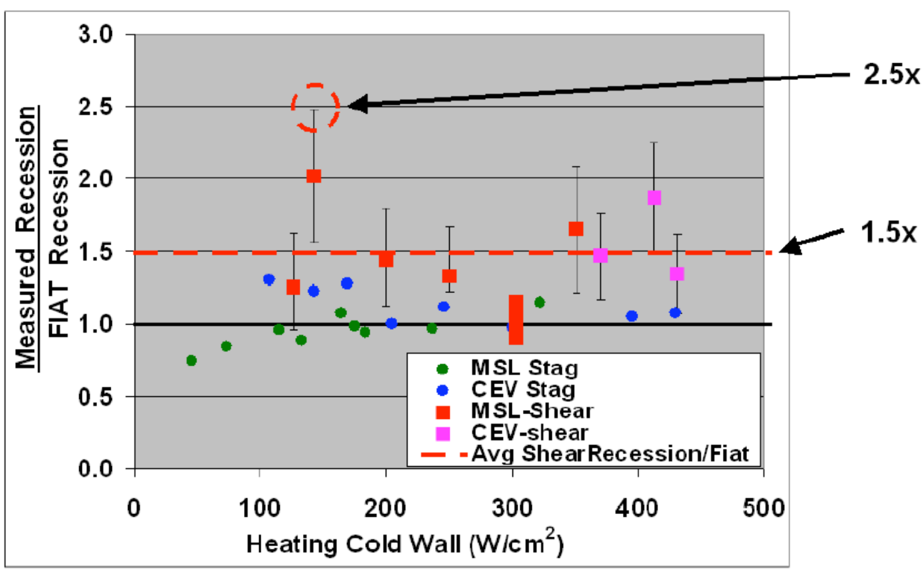


MSL/Mars2020 Heatshield

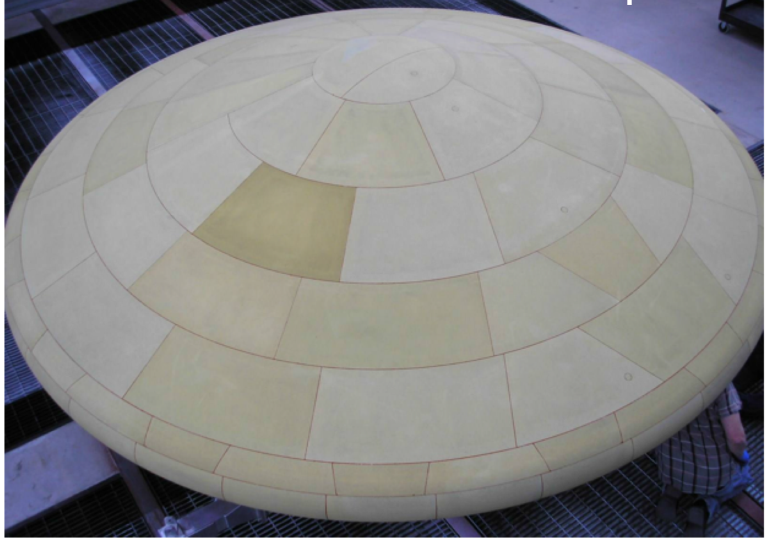
- Turbulent transition leads to peak heating occurring on the vehicle's leeside
- Heatshield made of PICA tiles with RTV gap fillers
  - Instrumented with thermocouple plugs (MISP sensors)
- Measured recession from PICA shear testing was significantly higher than model predictions (FIAT)
  - Led to inclusion of a 150% recession lien in MSL heatshield analysis and sizing
  - Later proved to be due to test coupon design
- MSL Flight data confirmed that nominal recession predictions are conservative at MSL conditions



Augmented PICA Recession in Shear Testing



MSL Tiled PICA Heatshield with RTV Gap Fillers



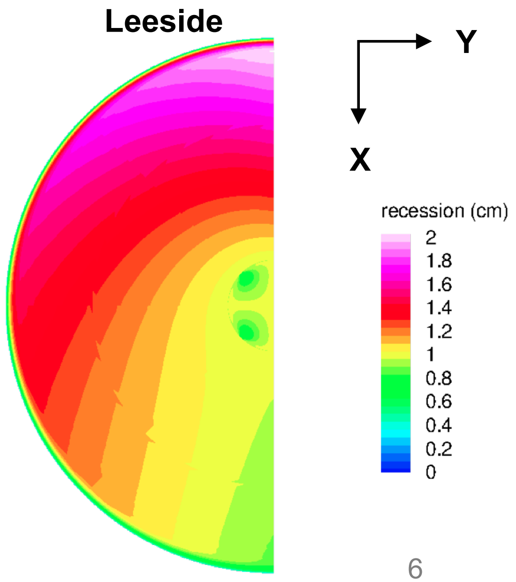
Heatshield Mass and Vehicle Balancing

- Entry vehicle mass properties requirements
  - Entry vehicle CG should be within +/-15 mm (ideally at 0 mm) radially from axis of symmetry at parachute deploy, (x,y)=(0,0) – Heatshield ablated
    - Off-center CG leads to vehicle oscillations under parachute (wrist mode)
  - Entry vehicle CG should be offset by EBMs from entry until shortly before parachute deployment to meet a hypersonic L/D requirement (AoA) – heatshield ablating during this time)
- Vehicle balancing analysis process
  - Unbalanced entry vehicle CG is determined on a spin table
    - Nominal heatshield mass loss distribution is included by analysis
  - Static balance mass is added to shift the CG to axis of symmetry (0,0)
  - EBMs are calculated for unablated EV to offset CG to achieve a target L/D (AoA)
  - CBMs are calculated to balance the vehicle to the desired CG location for cruise
- Monte Carlo analysis is performed by varying many performance parameters (including heatshield mass loss) to ensure that the dispersed vehicle state meets the requirements
- Accurate estimates of heatshield mass; its spatial distribution and its uncertainty are important for vehicle balancing throughout entry
  - Also important for heatshield separation and re-contact analysis

MSL Approach

- Recession was estimated at multiple points along the centerline based on margined design environments and including the recession lien
- Interpolations schemes were used to create full-heatshield recession map based on heating distribution (shown in bottom right)
- Integration of mass loss over heatshield produced a total mass loss of 56.6 kg
- To provide a measure of variability, 3 scenarios were assumed (table below)
    1. Recession occurs as predicted for the entire heatshield
    2. Only top half (leeside) of the HS recessed
    3. Only top third (leeside) recessed
- For balancing and Monte Carlo analysis, heatshield mass loss and corresponding CG were varied linearly between these three scenarios

Scenario	Description	Max Ablated Mass	Ablated CM @ Max Ablated Mass (Spacecraft CSYS)		
			x_c	y_c	z_c
		kg	*mm*	*mm*	*mm*
1	Max ablated mass	56.6	-199	0	1828
2	Only top half of HS recessed	32.3	-1041	0	1820
3	Only top third of HS recessed (in terms of diameter)	21.0	-1405	0	1760



Improvement Opportunities in MSL Approach

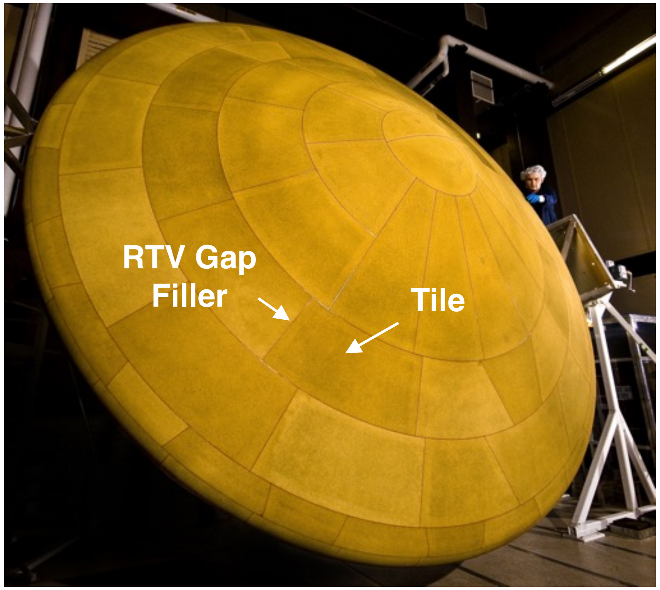
- MSL analysis did not include mass loss due to decomposition
  - Assumed to be negligible compared to recession mass loss
- Simplified approach to estimate spatial distribution of recession
  - TPS response simulations only done along centerline
- Conservative design assumptions lead to overestimation of mass loss and off-nominal balancing
  - Design environments used for heatshield sizing are conservative by nature (fully turbulent, supercatalytic, roughness augmentation, margins)
  - Recession lien (later investigation and flight data suggest that this lien is not required)
- Simplified approach for assessing variability
- For Mars2020, our goal is to improve upon MSL analysis and provide more accurate and realistic recommendations for total mass loss, its spatial distribution and variability
  - Reasonable fidelity within project resources

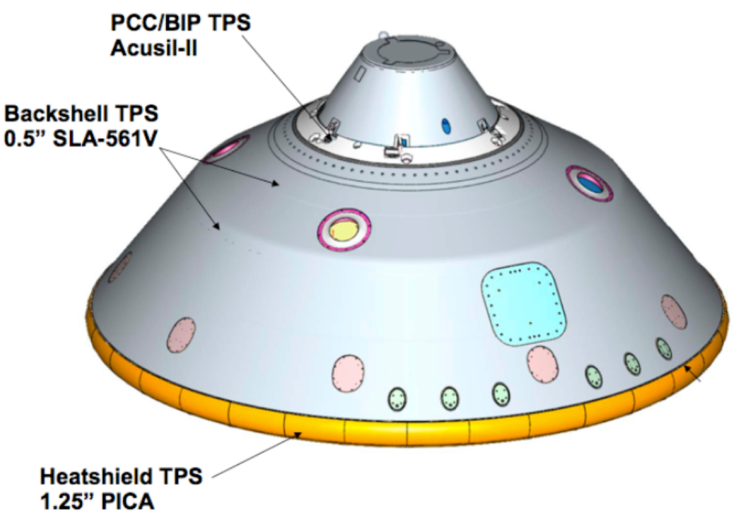
Mars2020 Approach

- Use unmargined heating environments to be closer to nominal expected response
  - Still conservative (fully turbulent, supercatalytic and includes roughness augmentation)
- Don't apply a recession lien (confirmed by MSL flight data)
- Employ a more accurate approach for determining the spatial distribution of mass loss
- Analysis process:
  - Perform TPS response simulations at discrete points distributed on the heatshield to estimate mass loss due to decomposition and recession
  - Polar interpolation between the analysis points to come up with a finer distribution of mass loss over the entire heatshield
  - Integrate mass loss distribution to arrive at total mass loss
  - Calculate CG of lost mass
- Provide a recommendation for mass loss variability

Study Limitations

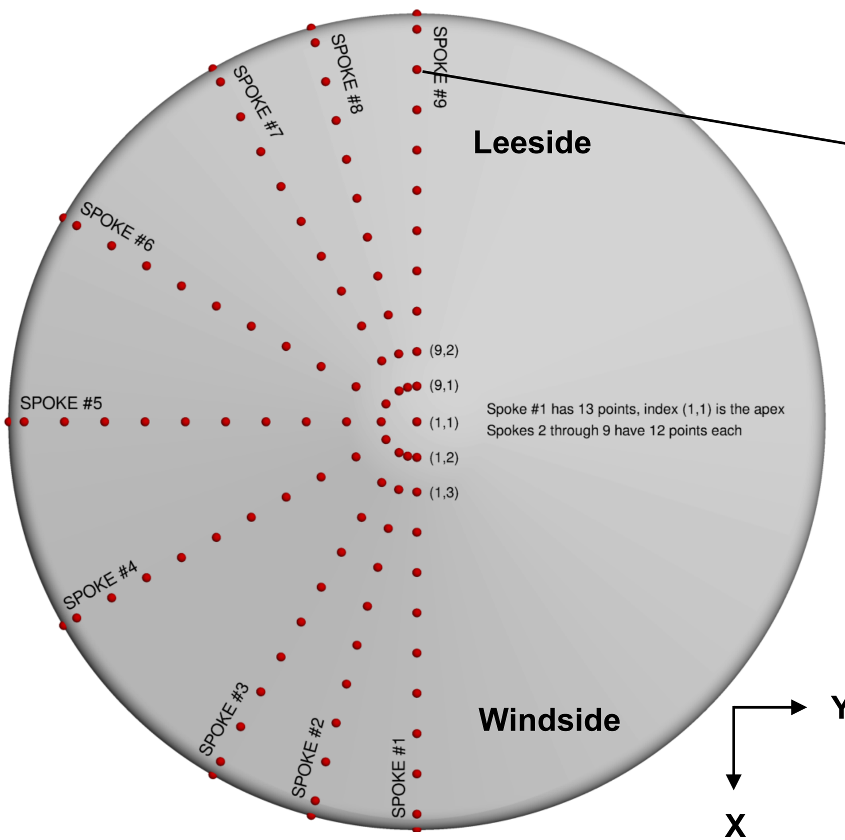
- This study does not account for mass loss of RTV gap fillers
  - The impact on total heatshield mass loss and CG should be small
  - Less than 5% of overall heatshield mass
  - Does not recede or pyrolyze as much as PICA
- This study does not account for mass loss of the backshell TPS materials
  - No recession at Mars2020 conditions
  - Heating conditions are significantly lower on the backshell, meaning that decomposition mass loss on backshell should be small compared to heatshield ablation
  - Distribution of mass loss expected to be more symmetric than heatshield

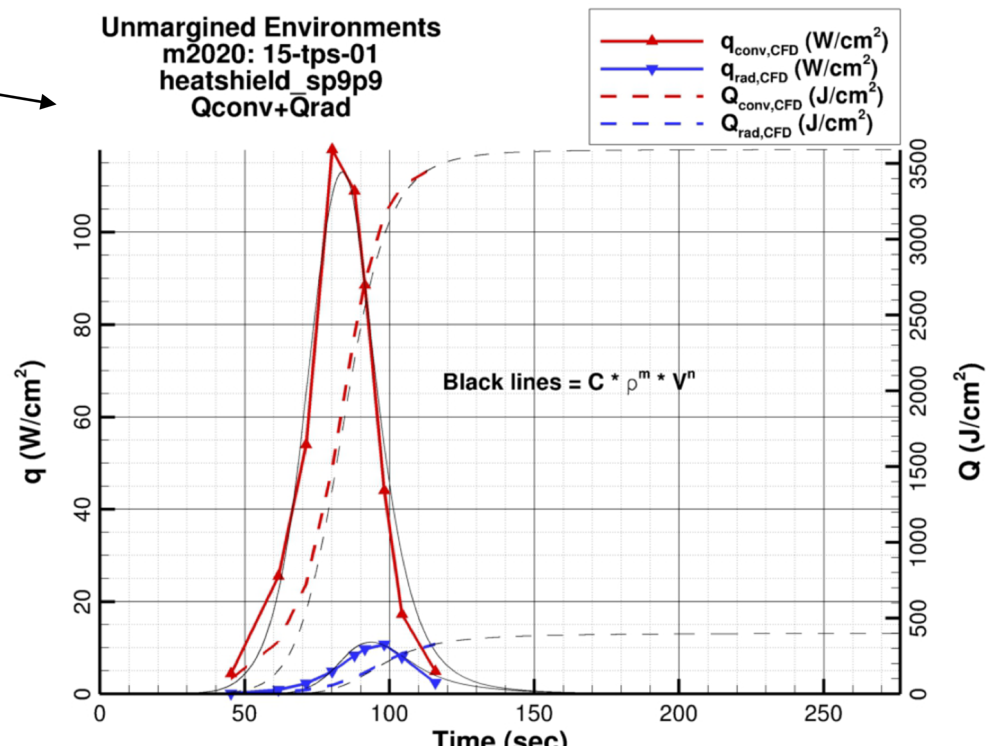




TPS Simulation Points

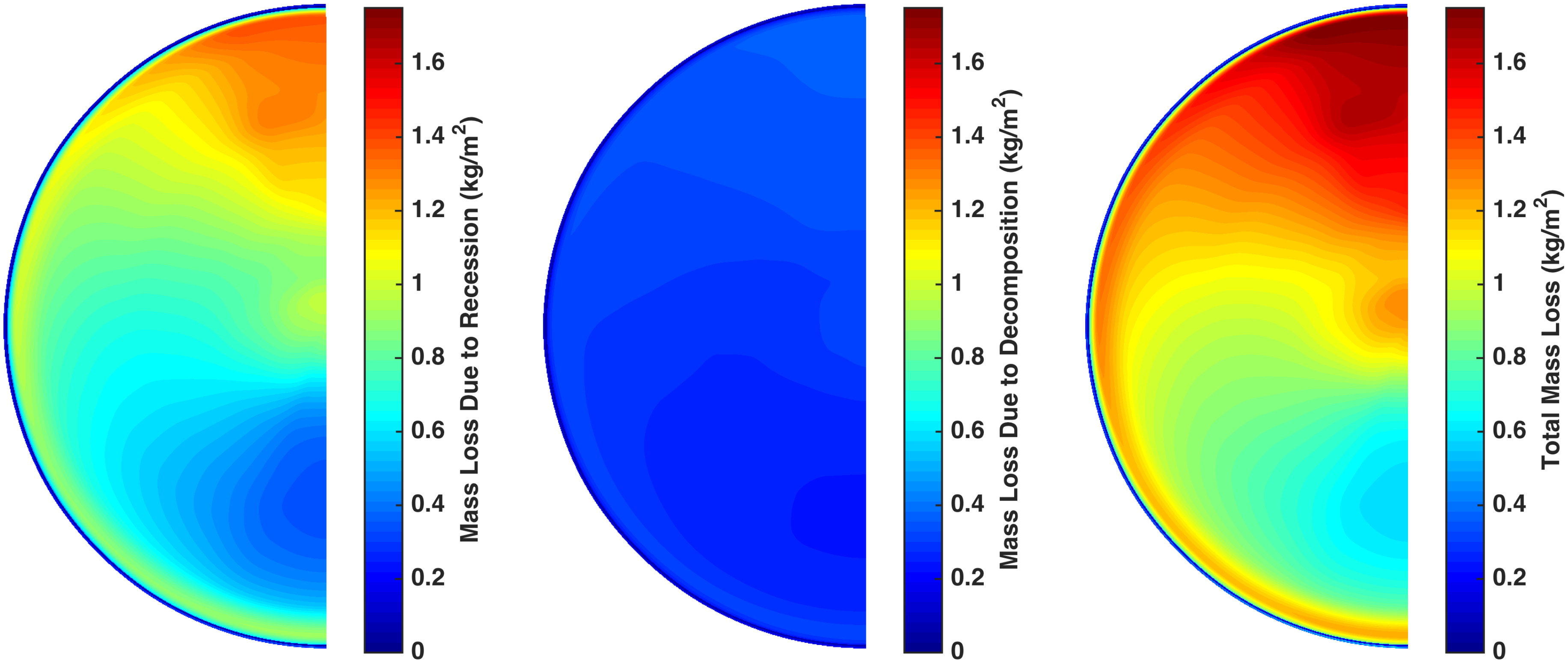
- Heating boundary conditions are extracted from CFD solutions at 109 points distributed along 9 spokes
  - Consider only half of the vehicle (symmetric heating across the pitch plane)
  - Environments are curve-fitted in time based on 9 CFD solutions
- FIAT simulations performed to estimate recession and decomposition mass loss at each point (integrated in time per unit area)





Mass Loss Distribution

- Interpolated estimated mass loss at discrete points to a finer resolution
- Integrated across the heatshield (multiplied by 2 for the full heatshield)
  - Integrated mass loss due to recession (full-heatshield): **13.94 kg**
  - Mass loss due to decomposition (full-heatshield): **5.32 kg**
  - Total Mass Loss (full-heatshield): **19.26 kg**

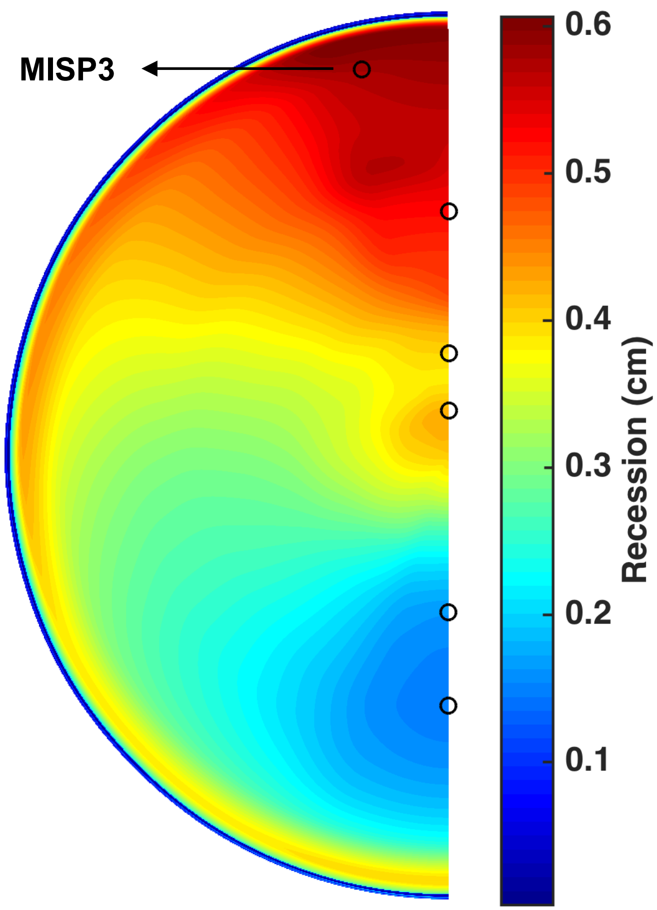


Recession Overprediction

- The equilibrium gas-surface chemistry model for PICA is known to overestimate recession at low heating conditions
  - Finite-rate regime
  - Recession map from mass loss analysis (shown here) is based on this model
- MSL heatshield was instrumented with PICA plugs containing 4 in-depth thermocouples at 7 locations (MISP plugs)
  - Shallowest thermocouple was at a nominal depth of 0.254 cm
- All shallow TCs survived indicating that MSL recession at MISP plug locations was less then 0.254 cm
- We can scale FIAT-calculated recession such that max recession at MISP locations is less than the depth of shallowest thermocouple
  - Max recession of 0.58 cm happens at MISP2-3 location
  - Scale the recession map by 0.254/0.58 = 0.438

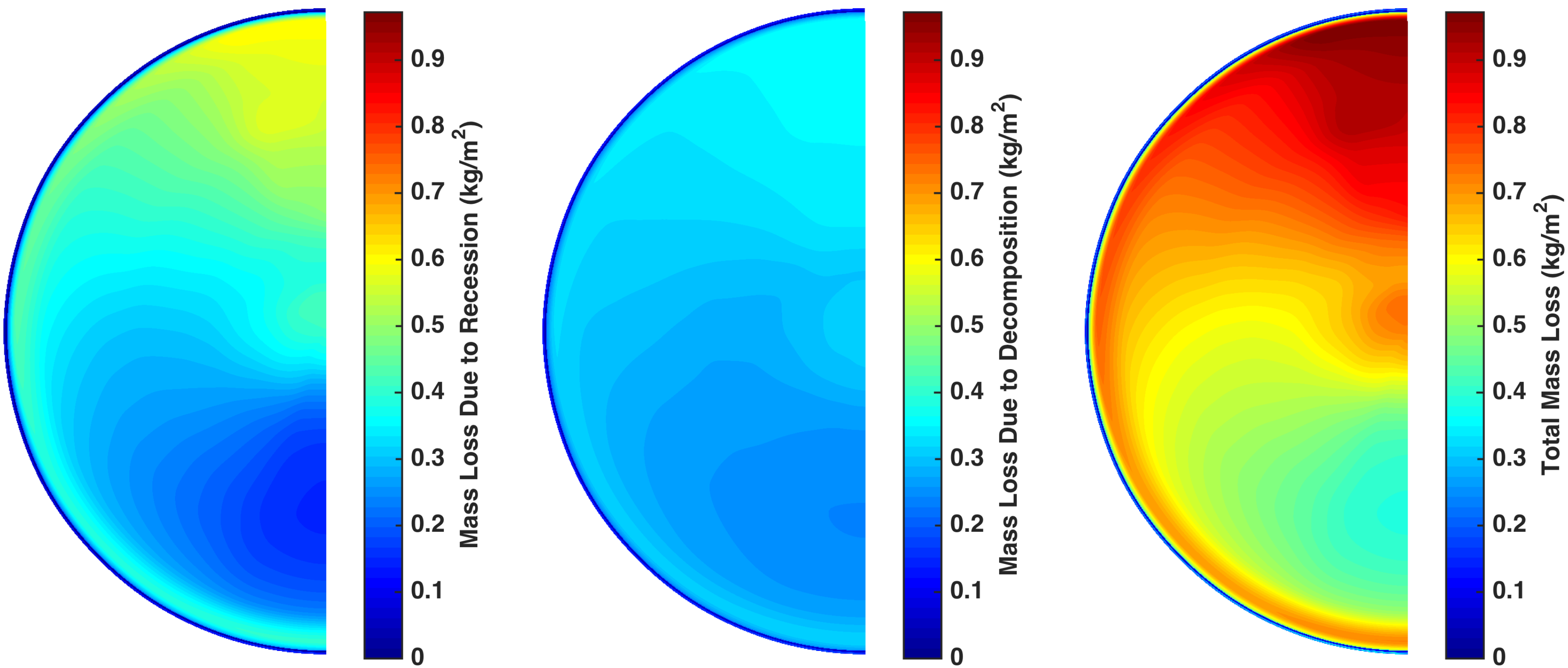
Recession Map from Mass Loss Analysis

Black Circles: MISP Sensors Location



Mass Loss Distribution (Scaled Recession)

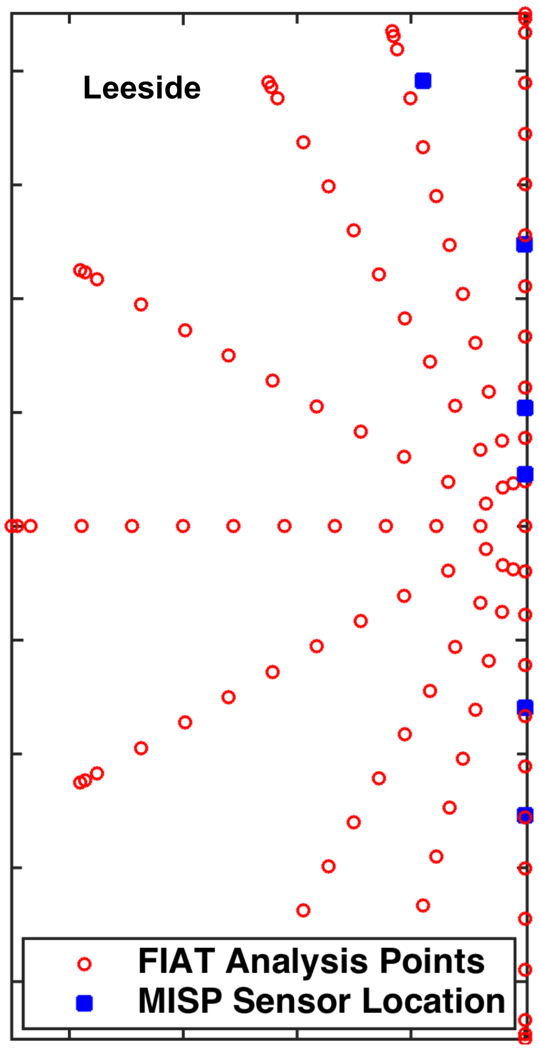
- Mass loss due to recession (full-heatshield): **6.11 kg**
- Mass loss due to decomposition (full-heatshield): **5.32 kg** (no change)
- Total Mass Loss (full-heatshield): **11.43 kg**



*Different color scale than figures shown earlier

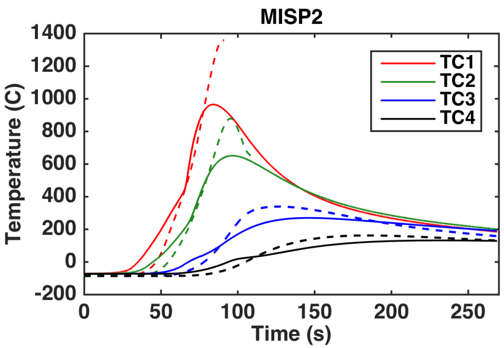
Comparison to MSL Flight Data (MEDLI)

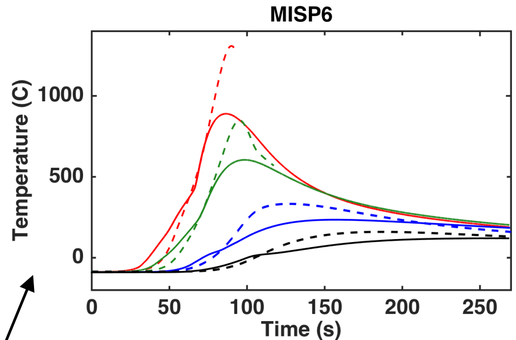
- FIAT simulations were done at locations near MISP sensors
- As a sanity check, the in-depth temperatures from our Mars2020 FIAT simulations can be compared with MSL flight data
  - No recession scaling in analysis results
- We should not expect a great match
  - Different trajectories (as-flown MSL vs. Mars2020 design)
  - Conservative heating assumptions in analysis
  - Overprediction of recession by PICA response model



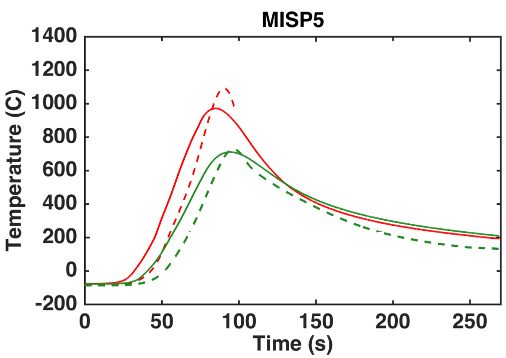
Comparison to MSL Flight Data

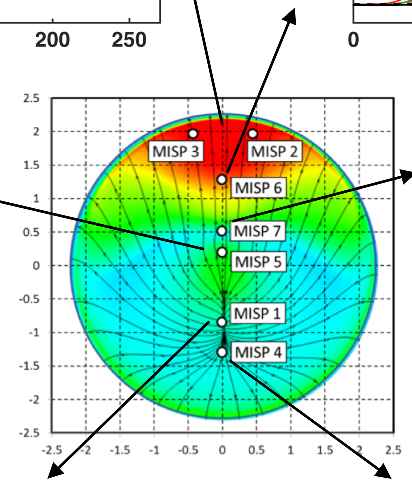
Dashed Lines: M2020 FIAT predictions
Solid Lines: MSL flight data

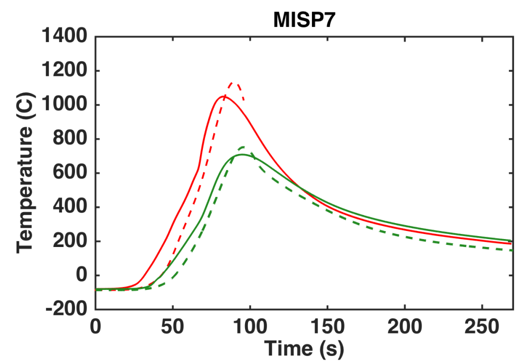


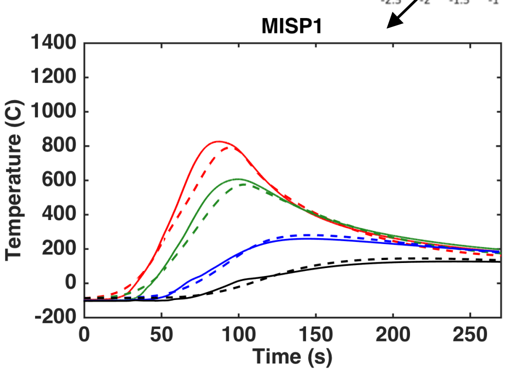


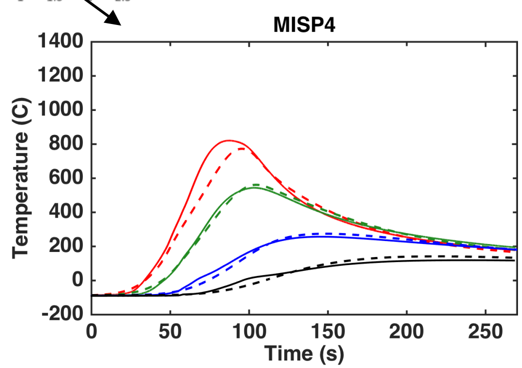
Mismatch due to recession overprediction and supercatalytic heating assumption







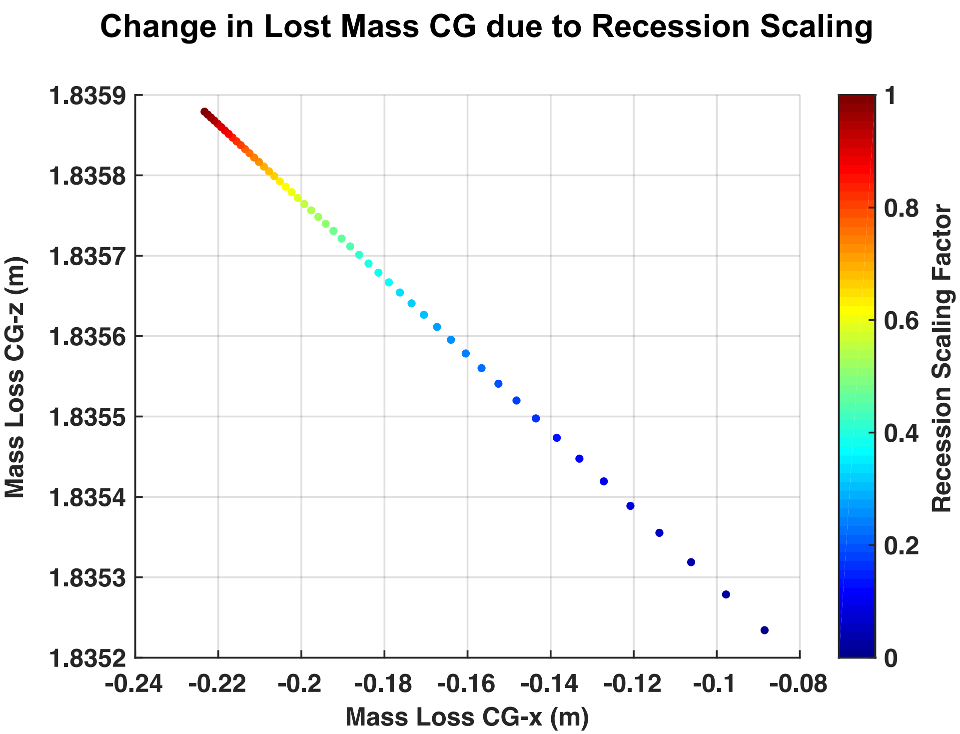




Close match with flight data in stagnation and apex regions provides confidence in decomposition mass loss predictions

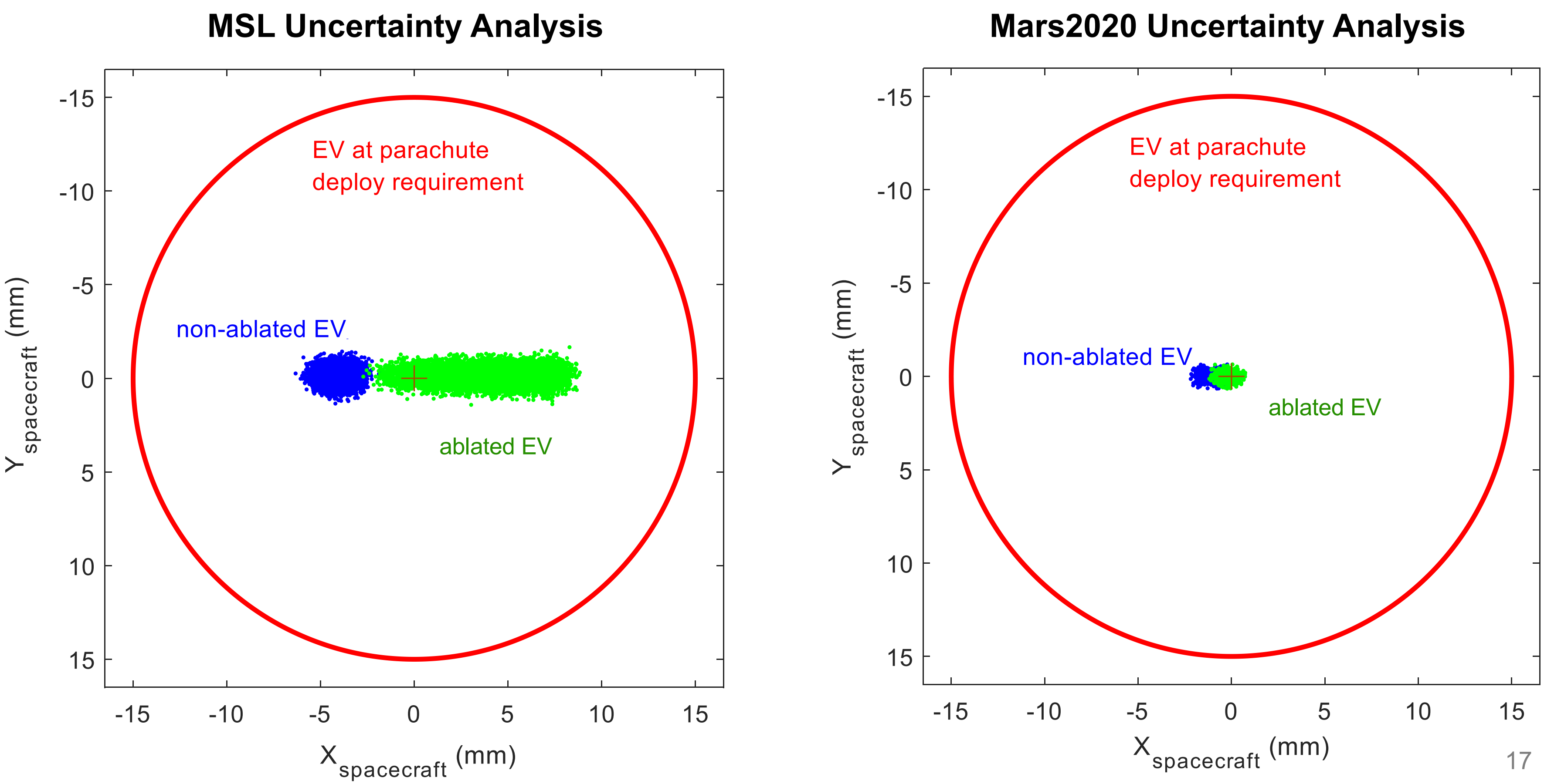
Final Recommendations

- Best-estimate total mass loss is **11.4 kg**
  - Corresponds to the case where recession was scaled to depth of shallowest thermocouple on MSL heatshield
- For Monte Carlo analysis, vary mass loss due to recession from zero to max recession (no scaling)
  - Upper bound of **19.3 kg**
  - Lower bound of **5.3 kg**
- As recession is varied, CG of lost mass shifts
  - CG-y =0 due to symmetric heating
  - CG-z is not very sensitive to recession scaling
  - CG-x moves toward the leeside as mass loss due to recession becomes a bigger part of total mass loss



CG Requirement at Parachute Deploy

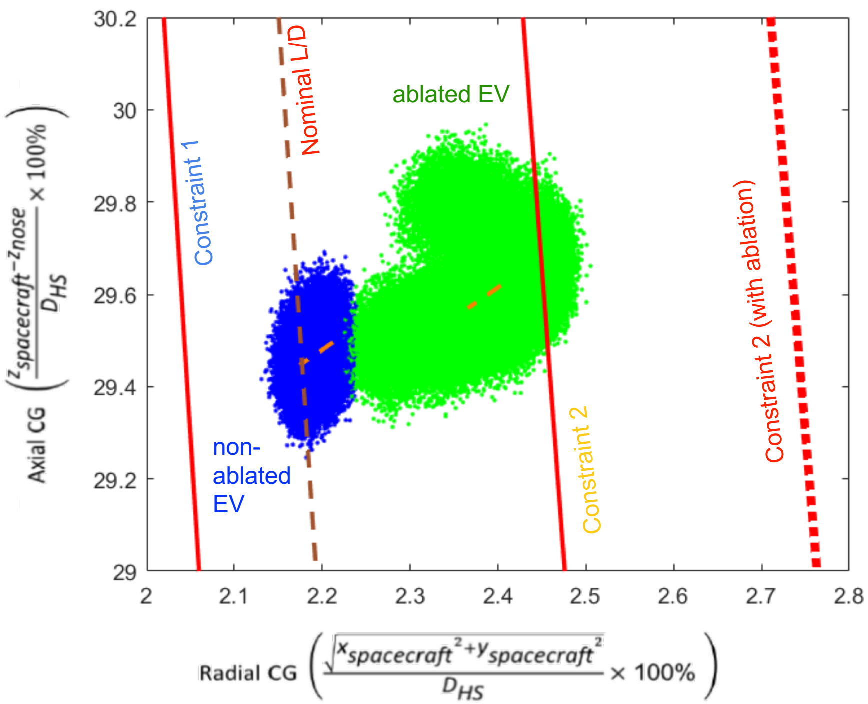
- Balance Mass that will be installed on EV is applied to all the unbalanced EV cases in uncertainty analysis to create an uncertainty cloud of possible EV CGs
- The large scatter in MSL analysis forced engineers to balance the vehicle to off-nominal CG
- Mars2020 data shows much more confidence that CG of the EV at parachute deployment meets requirements
  - Ample margin is available



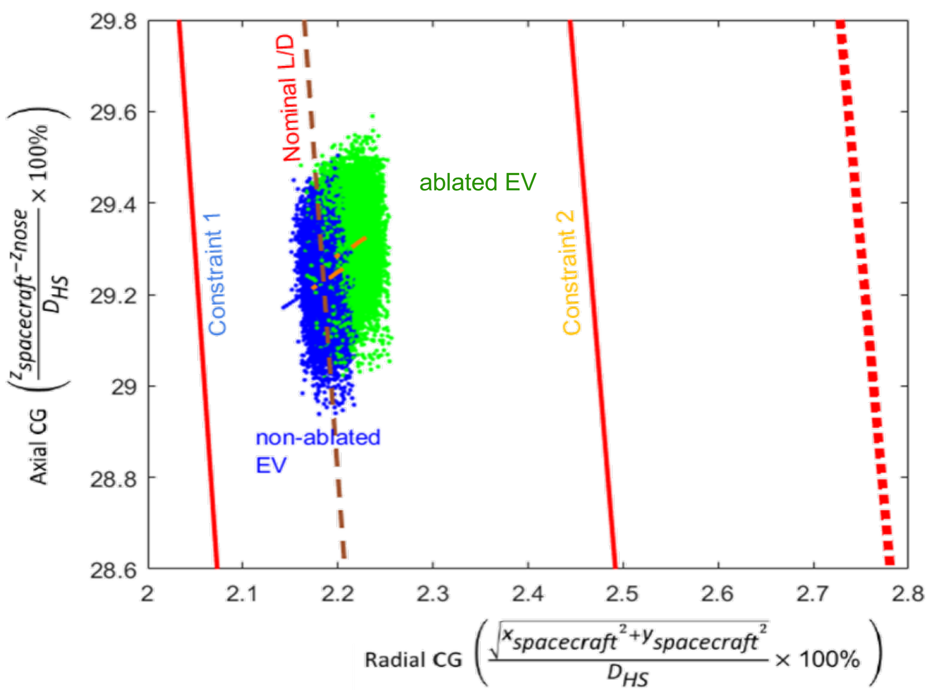
L/D Requirement

- Since EBMs are calculated for non-ablated vehicle, non-ablated cases (blue) surround the nominal L/D req. while ablated cases end up off nominal
- On MSL, ablation uncertainty was so high that new L/D requirement was added (the very right line) to accommodate ablation uncertainty
- With M2020 mass loss analysis, we have more confidence that even ablated cases will fall close to Nominal L/D requirement

MSL Uncertainty Analysis



Mars2020 Uncertainty Analysis



Summary

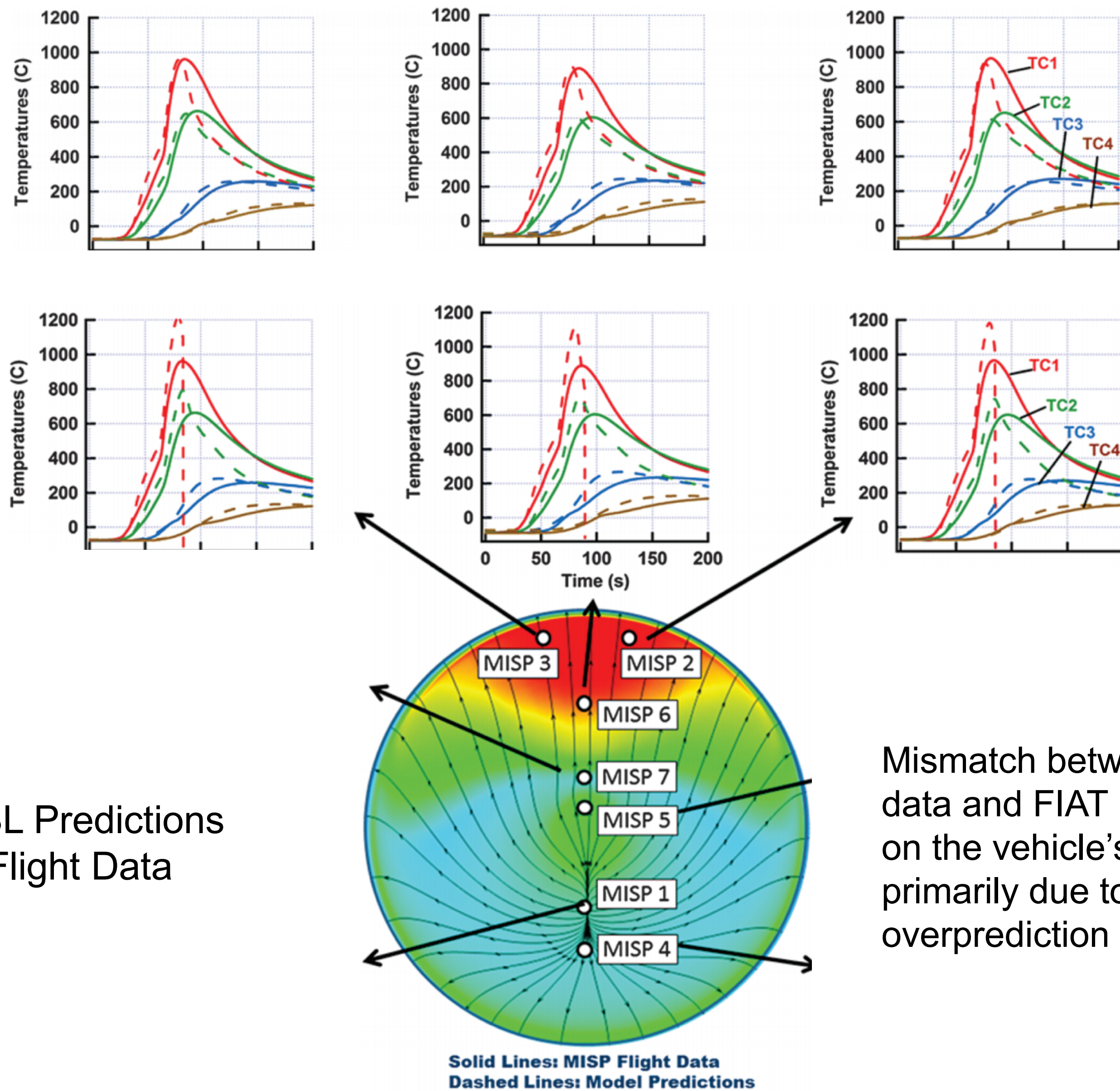
- Mars2020 analysis provides more accurate and realistic recommendations for total heatshield mass loss, its spatial distribution and variability compared to MSL analysis
- Uncertainty analysis showed that the CG requirement at parachute deploy and the L/D requirement can be satisfied with ample margin

Questions?

Flight Data Compared to MSL Predictions With and Without Recession

Without Recession

With Recession



Dashed Lines: MSL Predictions
Solid Lines: MSL Flight Data

Mismatch between flight data and FIAT predictions on the vehicle's leeside is primarily due to recession overprediction

What Constitutes as Mass Loss?

Heatshield Material Can Lose Mass in Two Different Ways

1. **Recession**: mass loss due to removal of material from ablator's surface
   - Chemical reactions between the ablator and boundary layer gases (ex. Carbon oxidation, primary mode of recession for PICA at MSL conditions)
   - Material phase change (melting, sublimation)
   - Mechanical removal of material under pressure/shear
2. **Decomposition**: as heat penetrates in-depth, certain components decompose and lose mass by releasing gases that permeate to surface

Common Misconception: Ablation was almost non-existent on MSL vehicle according to measured data

- The only information available from flight data is that recession was less than 0.1" at MISP sensor locations
- Conservative design assumptions led to pre-flight recession predictions as high as 0.8"; however, more realistic assumptions lead to 0.14" of max recession at MISP sensor locations
- MSL might have had recession as high as 0.1" in addition to mass loss due to in-depth decomposition

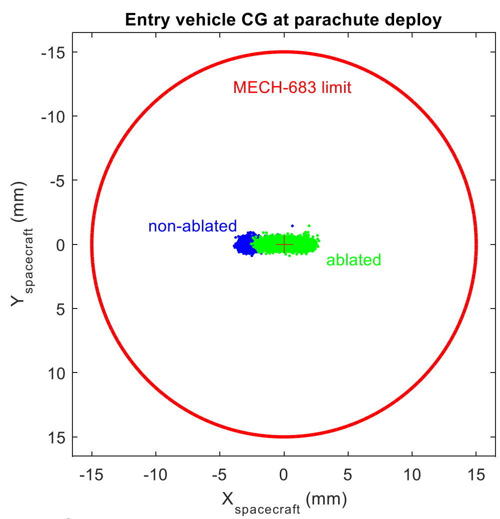
Ablation = Recession + Decomposition
MSL had non-zero recession and decomposition

FIAT Simulation Assumptions

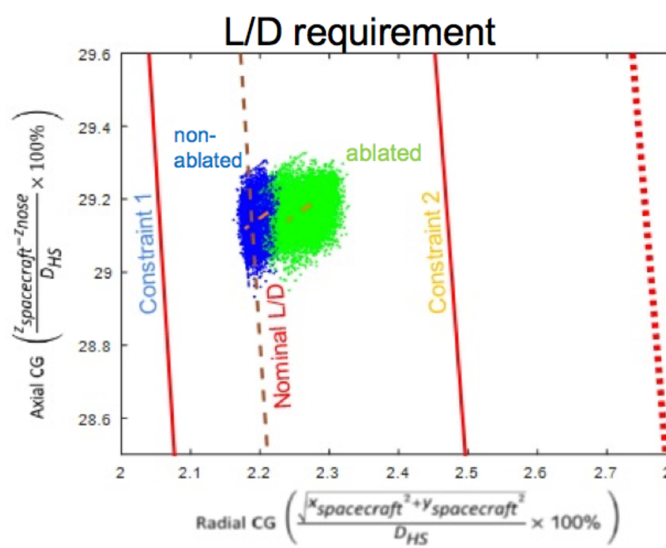
- 15-TPS-01 trajectory
- Unmargined environments based on LAURA/HARA simulations
  - Fully turbulent, supercatalytic, roughness augmentation
  - Includes radiative heating
  - No margins
- 1D thermal analysis of PICA using NASA Ames code FIAT
- Substructure stack
  - Using the same substructure stack for all analysis points
  - Mass loss not very sensitive to substructure stack
- Initial temperature of 3 C used for the entire heatshield
  - Mass loss not very sensitive to initial temperature
  - Performed the analysis using minimum TPS temperature from MSL flight data; mass loss sensitivity was on the order of 1-2%
- Mass loss is calculated at heatshield separation
  - Same results at parachute deploy
  - Semi-automated analysis process allows quick turnaround of mass loss estimation at other trajectory times

What Is Currently Done for M2020?

- From MSL flight data, we know that recession was overestimated
- Based on back-of-the-envelope calculations, heatshield mass loss was reduced for Mars2020 simulations
  - Scenario 3 mass loss estimate from MSL (~21 kg) was reduced to 7.6 kg based on a simple scaling of recession (removing recession lien)
- For downstream analyses (ex. balance mass calculations), mass loss is assumed to be between 0 and 7.6 kg with an average of 3.8 kg
  - This is probably too low. 7.6 kg was supposed to be the best-estimate
  - Mass loss of 0 kg is not physically possible
- Static balance mass is calculated to balance the vehicle at parachute deploy
- EBMs for every Monte Carlo case are found by balancing the non-ablated vehicle to nominal L/D target requirement



Source: JPL



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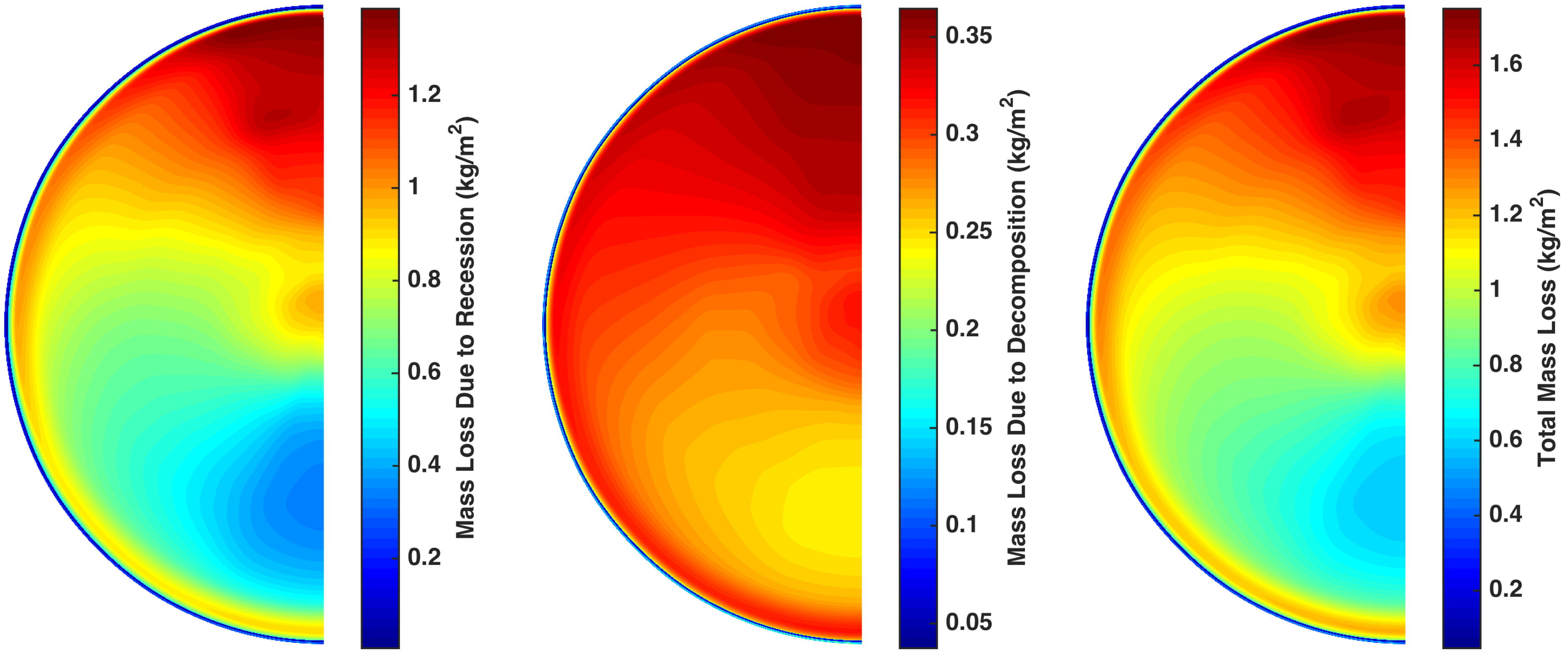

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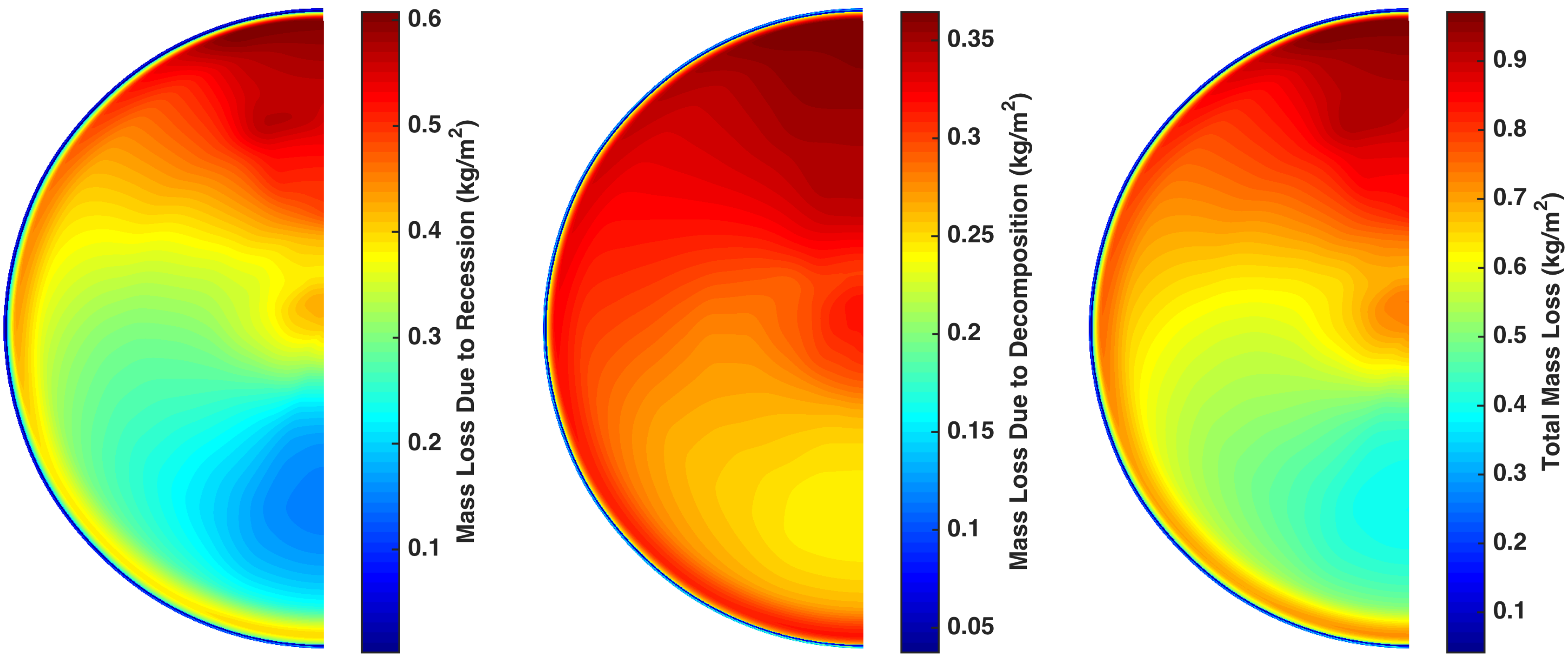

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