Preliminary Reentry Trajectory, Aeroheating, and TPS Sizing Predictions for the Inspiration Mars Mission

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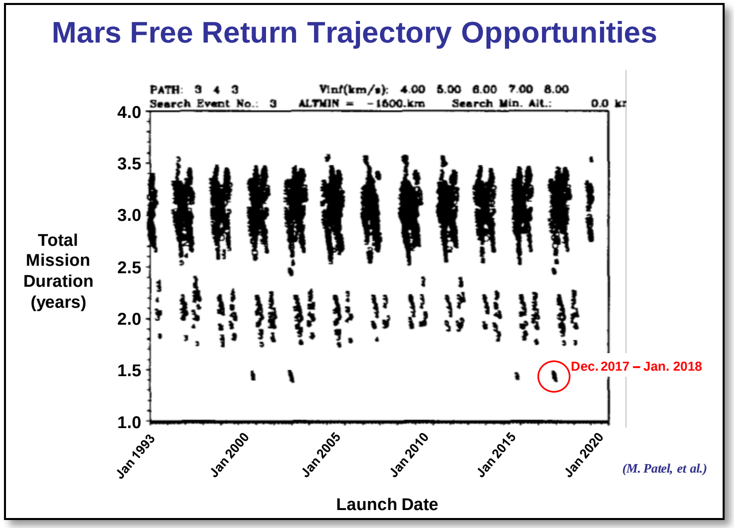
Outline

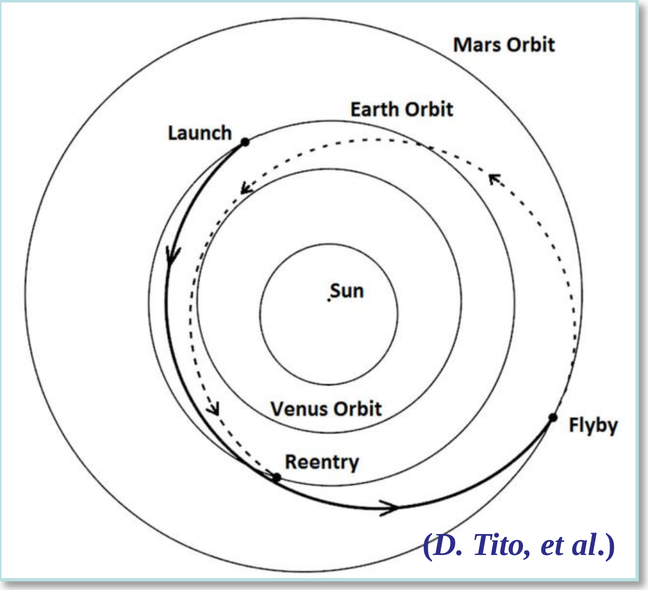
- Inspiration Mars Mission Concept
- Ames Support
- Baseline Reentry Concepts and Assumptions
- Trajectory/Aerothermal Results
- TPS Material Response and Sizing Results
- Conclusions and Future Work

The work presented here was performed in collaboration with Paragon Space Development Corp., Applied Defense Solutions Inc., and Space Exploration Engineering Corp. under a Reimbursable Space Act Agreement (SAA2-402751) in support of the Inspiration Mars Foundation

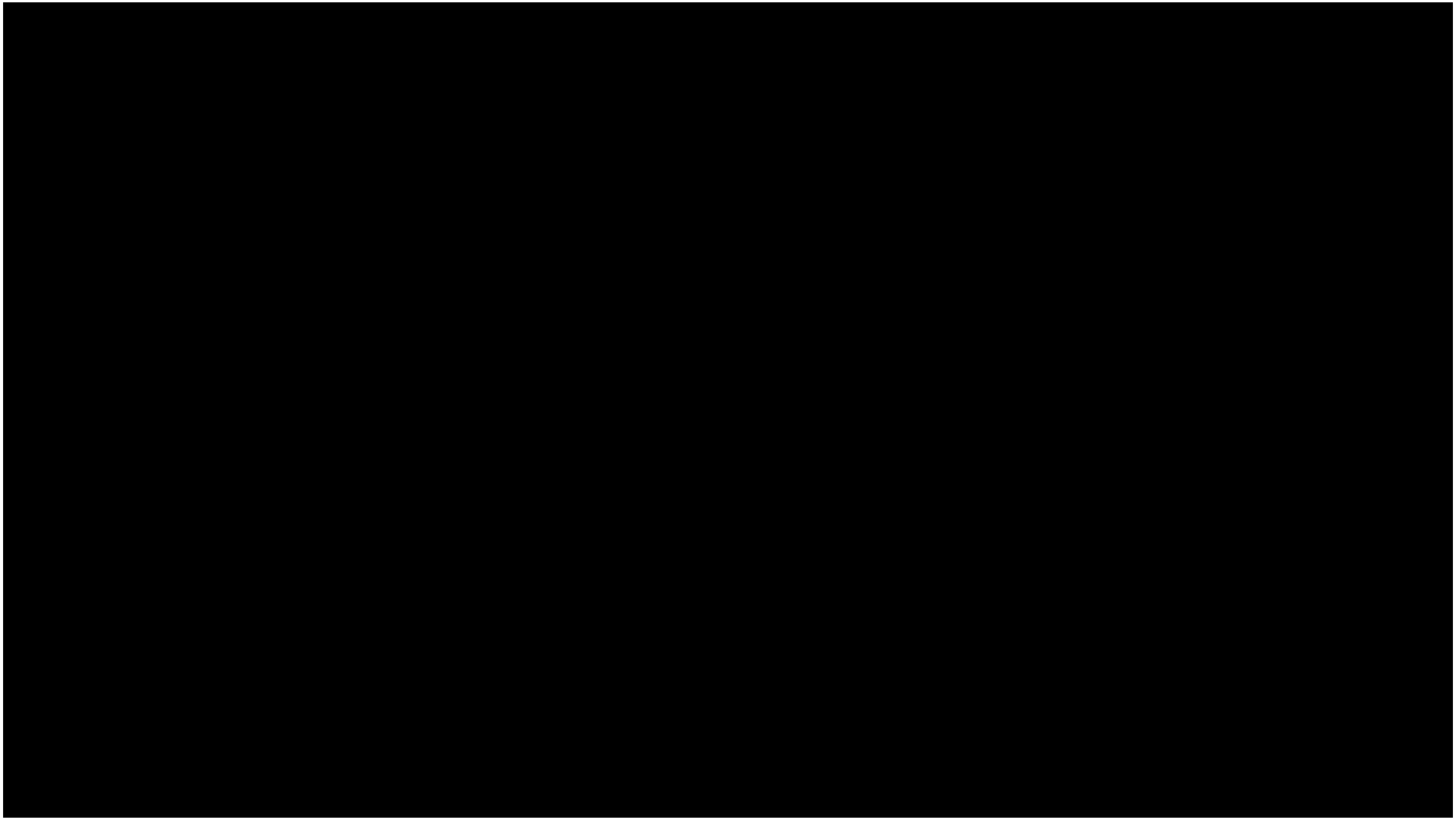
Inspiration Mars Mission Opportunity

- Concept developed by a team lead by Dennis Tito – the “first space tourist”
  - Mission is outlined in a paper presented at the IEEE Aerospace Conference
  - Team includes members from Paragon Space Development, Applied Defense Solutions, Space Exploration Engineering, and others
- Every 15 years, a set of “free-return” Mars fly-by's is possible with relatively short flight times
  - These trajectories leave Earth, fly close to Mars, and then return to Earth without any deterministic maneuvers
  - Most of these trajectories have total flight times of 2 to 3 years
  - Next opportunities for short free return missions are in 2015 and <u>2018</u>
  - Total mission time for these opportunities is <u>501 days</u>



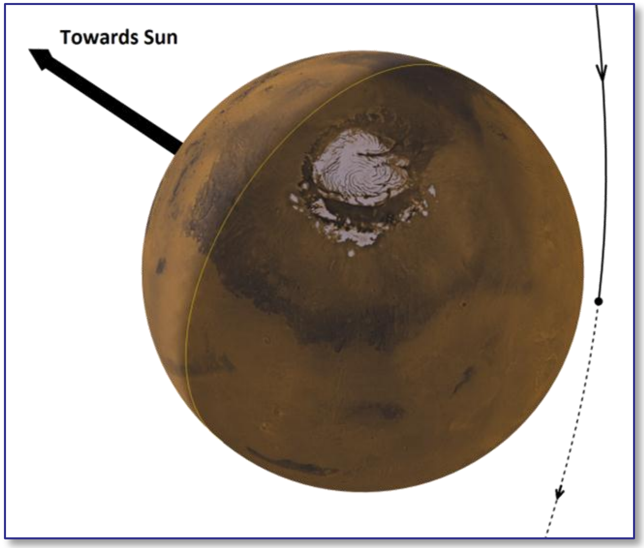


Inspiration Mars 501-Day Trajectory



Baseline Mission

- A 501-day "free-return" Mars flyby passing within a hundred miles of the surface of Mars
  - Only small correction maneuvers are needed during transit
- "Simple" mission architecture
  - Crew of two, man and woman
  - No orbit of Mars or entry into Mars atmosphere
- Mission trajectory highlights
  - Launch Jan 5, 2018
  - 1.4 years duration (501 days)
  - Mars on 20 Aug 2018 (227 days duration)
  - Earth on 20 May 2019 (274 days duration)
  - At Mars, Earth is 38,000,000 miles away
  - Within 100,000 km of Mars for ~10 hours
  - Return trajectory falls near the orbit of Venus
- Earth return reentry speed is 13.7 km/s!
  - Compared to 8 km/s for LEO return and 11 km/s lunar return



Flight Architecture Concepts

- Baseline launch, flight and reentry architecture options being evaluated now
- Habitat module used during mission and detached prior to reentry
  - Investigating several possibilities
- Select features and requirements
  - Crew of two – man and woman
  - No extra vehicular activity
  - Critical components located internal to vehicle
  - Subsystems designed for simplicity and “hands on” maintenance, and repair

- All primary vehicle systems have some "heritage", with exception of:
  - Long-duration Environmental Control and Life Support Systems (ECLSS)
  - *Perhaps* thermal protection system (TPS) on the reentry vehicle

Critical Issue: Reentry Heating

- Fast, free-return trajectory means that the crew capsule reenters Earth's atmosphere at a relative speed of 13.7 km/s!
- Magnitude of stagnation heating is dependent on a variety of parameters, including reentry speed (V), vehicle effective radius (R), and atmospheric density (ρ)

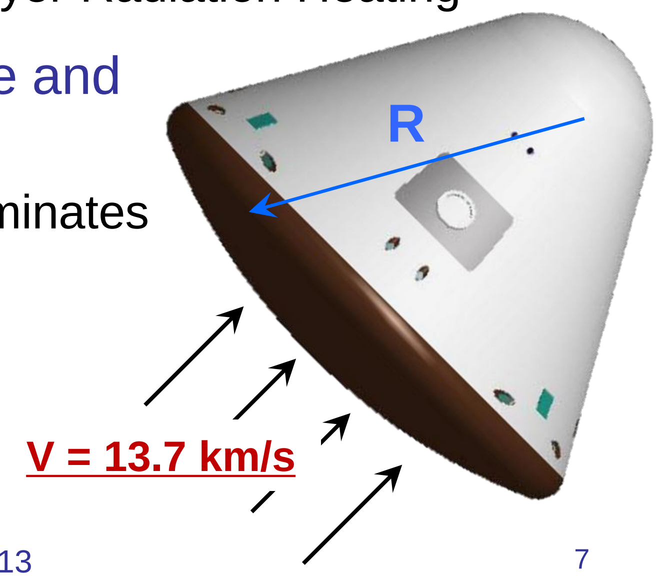
$$\dot{q}_{conv} \propto V^3 \left(\frac{\rho}{R} \right)^{0.5}$$

Convective Heating

$$\dot{q}_{rad} \propto V^8 \rho^{1.2} R^{0.5}$$

Shock Layer Radiation Heating

- As reentry speed increases, both convective and radiation heating increase
  - At high speeds, radiation heating quickly dominates
- As the effective vehicle radius increases, convective heating decreases, but radiation heating increases



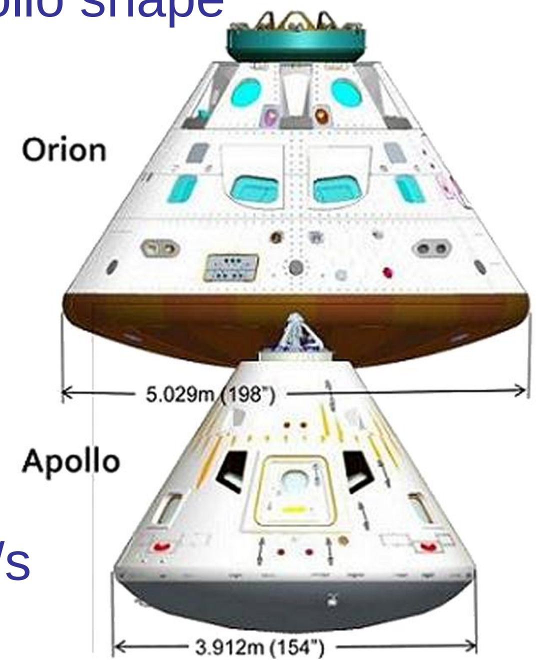
Ames Support

- Recognizing the challenge for the reentry phase, the IM team contracted with Ames, through a Reimbursable Space Act Agreement (RSAA), to assess the reentry environment
- Phase I tasks include:
  1. Determine reentry flight trajectories
  2. Predict aeroheating environments
  3. Predict TPS material performance and thickness
  4. Assess the capabilities of analytical tools and test facilities to support the IM mission

- Additional phases of work may include:
  - More detailed analyses of reentry vehicle point designs
  - Ground testing to validate analysis tools and verify TPS material performance

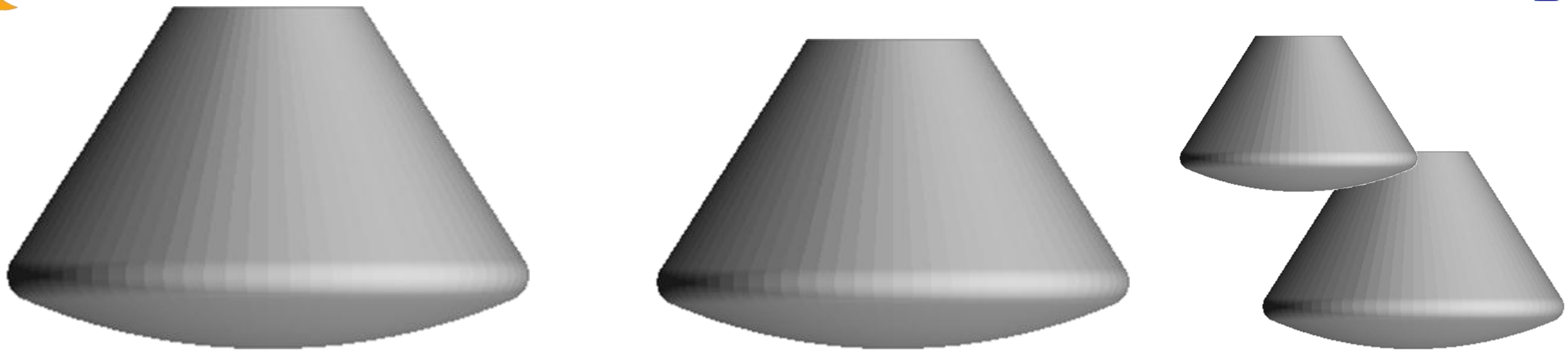
Trajectory/Aeroheating - Parameters

- Reentry vehicle capsule geometry is similar to Apollo shape
  - Blunt sphere-cone with spherical heatshield
  - 32.5º cone half-angle
- Several vehicle base diameters and entry masses were analyzed
  - 2.3 m and 2.9 m Gemini at 2000 kg
  - 4.56 m Boeing CST-100 at 5000 kg and 7500 kg
  - 5.03 m Orion at 6000 kg and 10,000 kg
- Relative reentry speeds of 13.3 km/s and 13.7 km/s
  - Best guess at possible range of speeds



- Vehicle L/D 0.25 (average number for this class of vehicle)
- Flight trajectory heading east along the equator (pro-grade)
- For each entry condition:
  - Pick the mid flight path angle for the nominal case (γ = -6.0º to -6.6º)
  - Investigate g-load hold (G-Hold) and altitude-hold (H-Hold) trajectories
  - Report max g, max heat flux, heat load

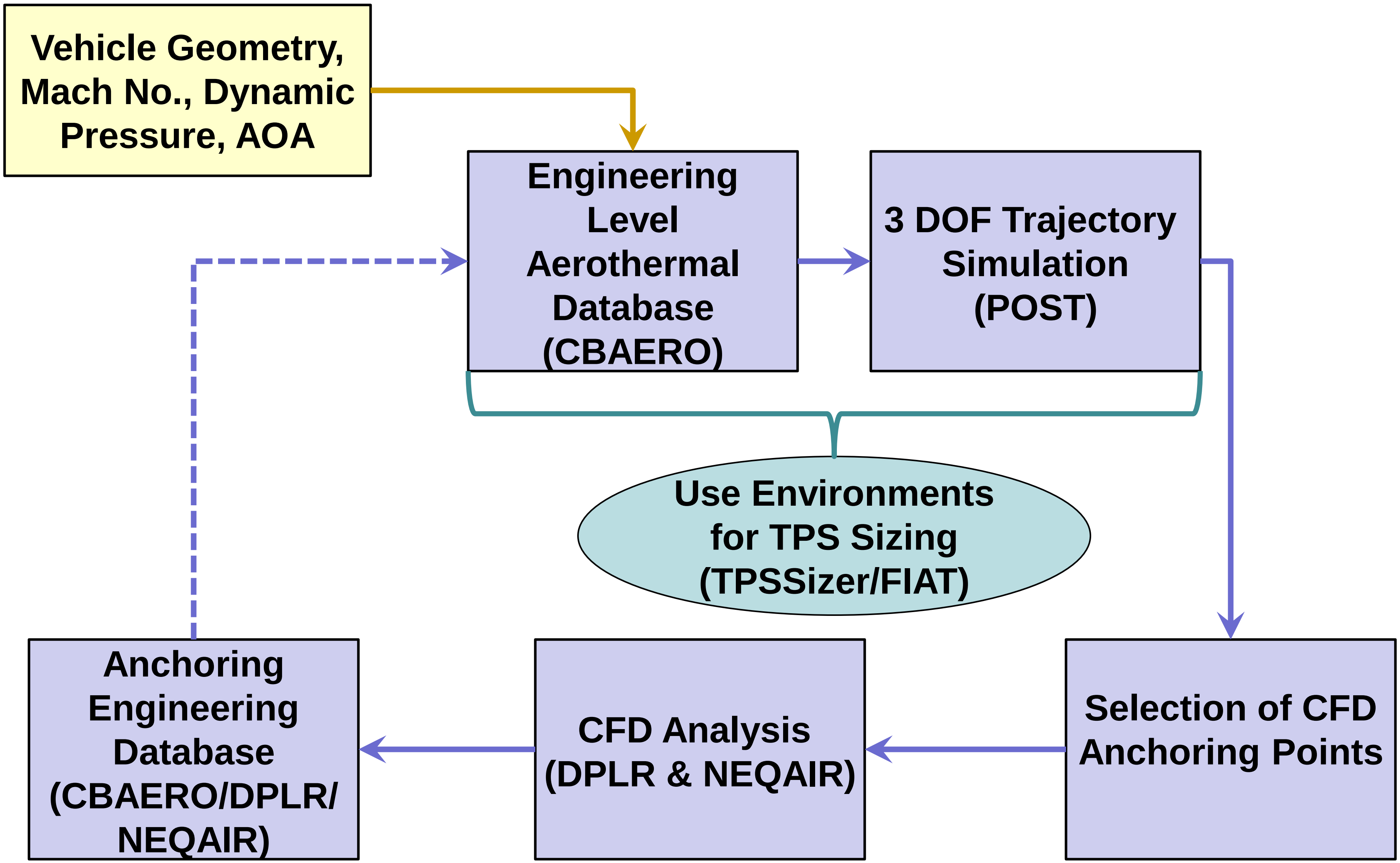
Aerothermal Database



Orion size	**CST-100 size**	**Gemini size**
5.03 m	**4.56 m**	**2.30 m & 2.90 m**
6000 & 10000 kg	**5000 & 7500 kg**	**2000 kg**

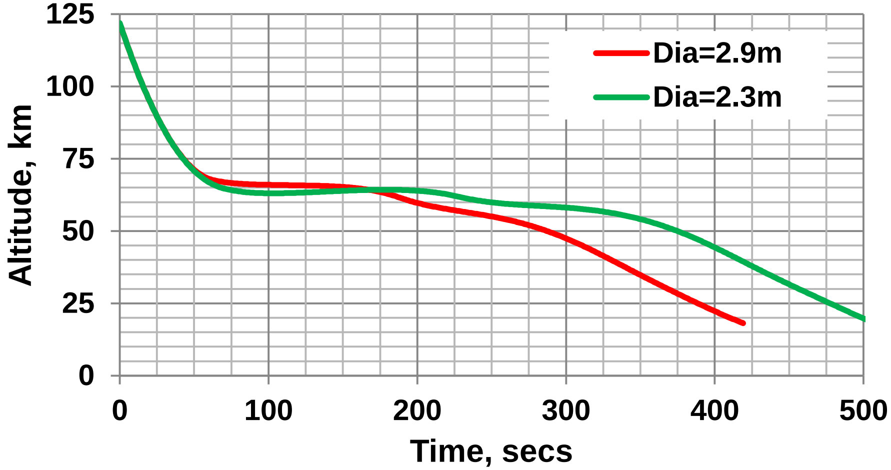
- Engineering level databases used to predict aeroheating loads
  - CBAERO 5.0
  - Mach numbers from 1.3 to 55
  - Full dynamic pressure coverage
  - Single angle of attack of 17º --> L/D = 0.25
  - Databases are anchored with high-fidelity CFD and shock radiation predictions using DPLR and NEQAIR
  - Margin factors used in aeroheating environment comparisons
    - 1.5 on turbulent convective heating
    - 2.0 on shock layer radiation

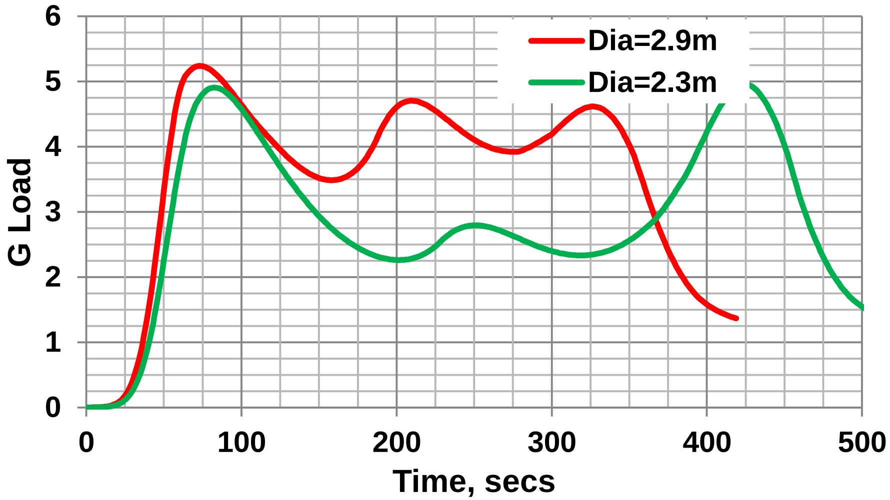
Aeroheating Database Process

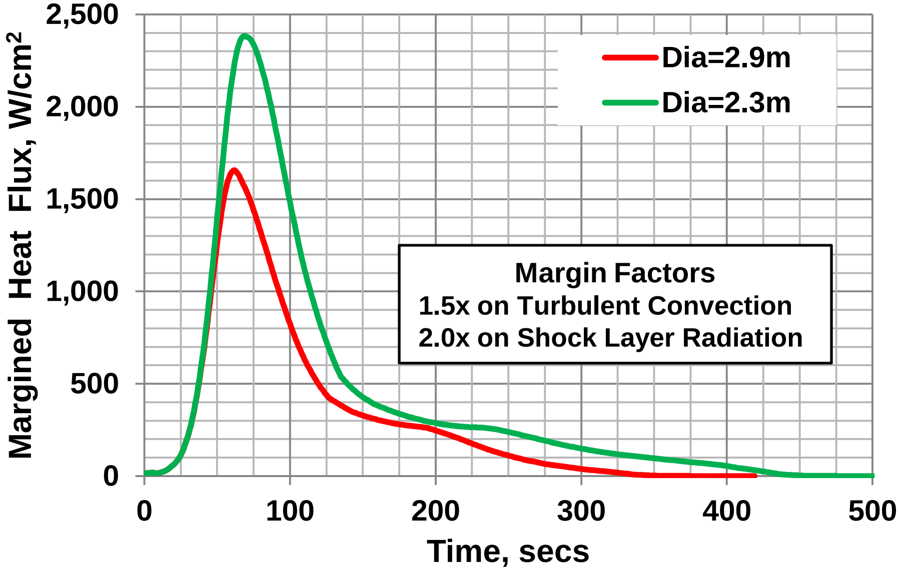


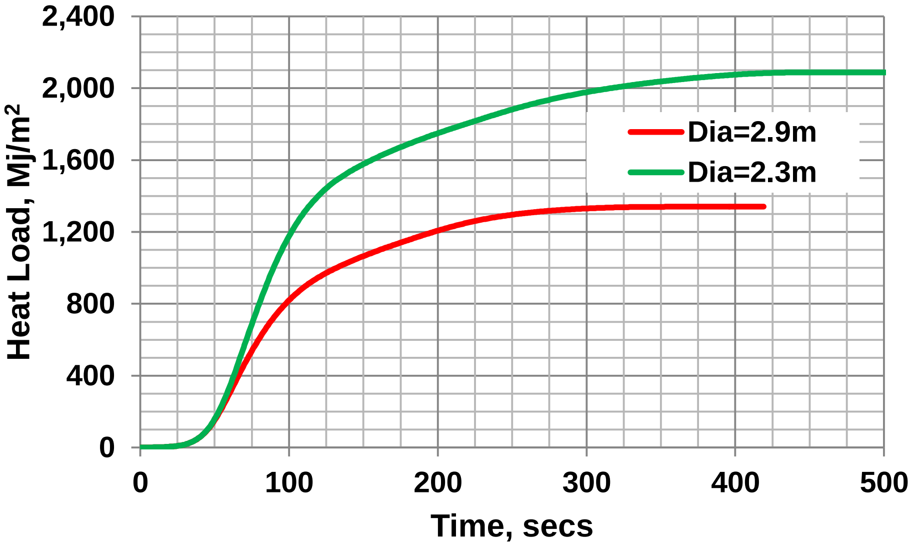
"Gemini" cases at 13.7 km/s and 2000 kg

- H-hold trajectories



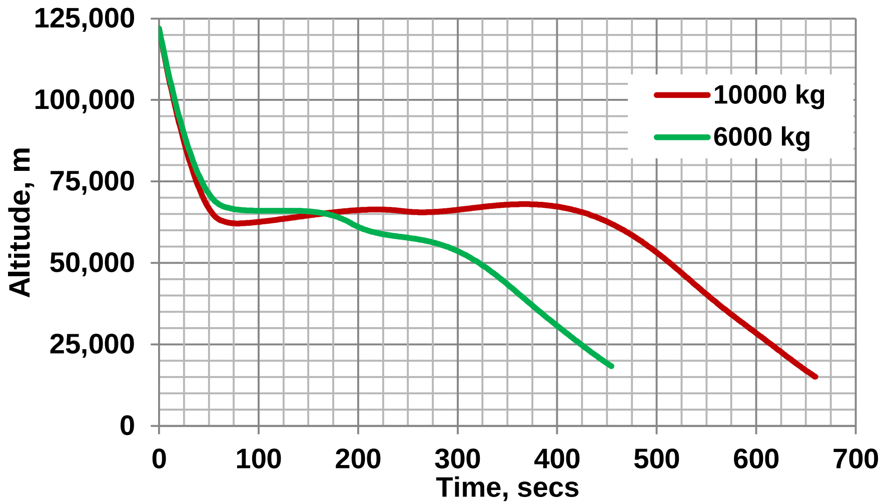


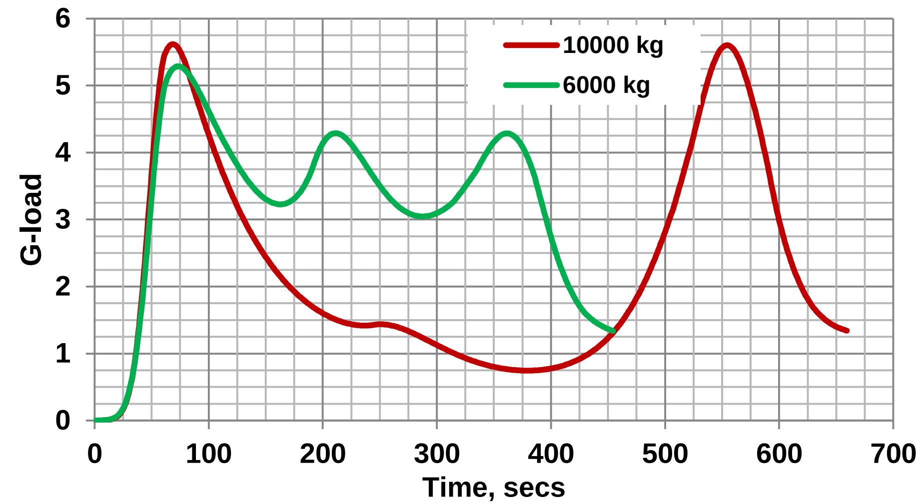


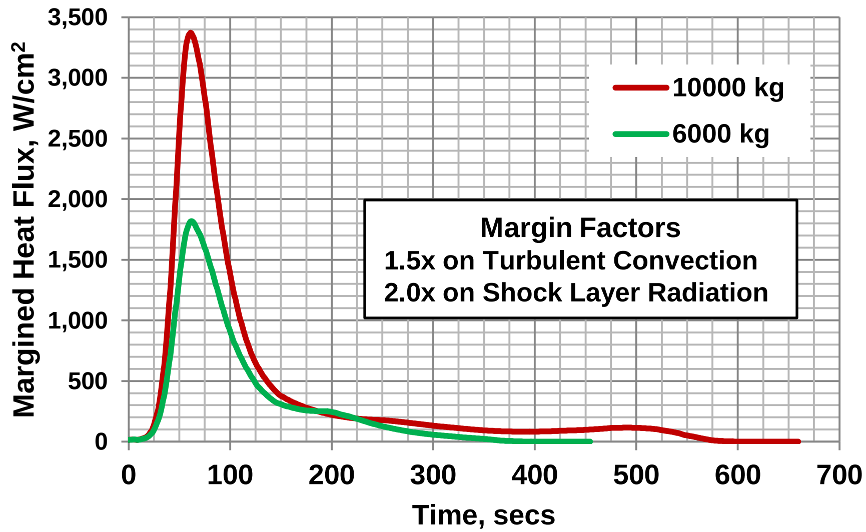


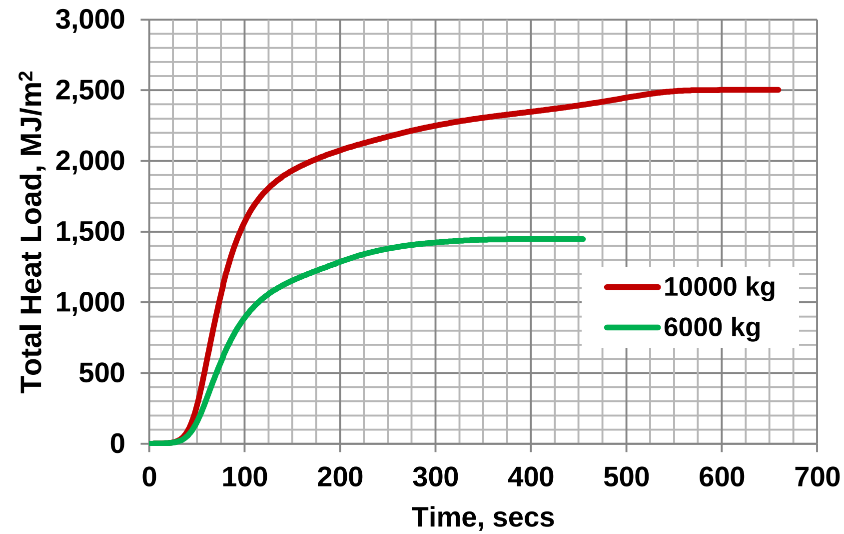
Orion cases at 13.7 km/s

- H-hold trajectories









Summary of Aeroheating Results

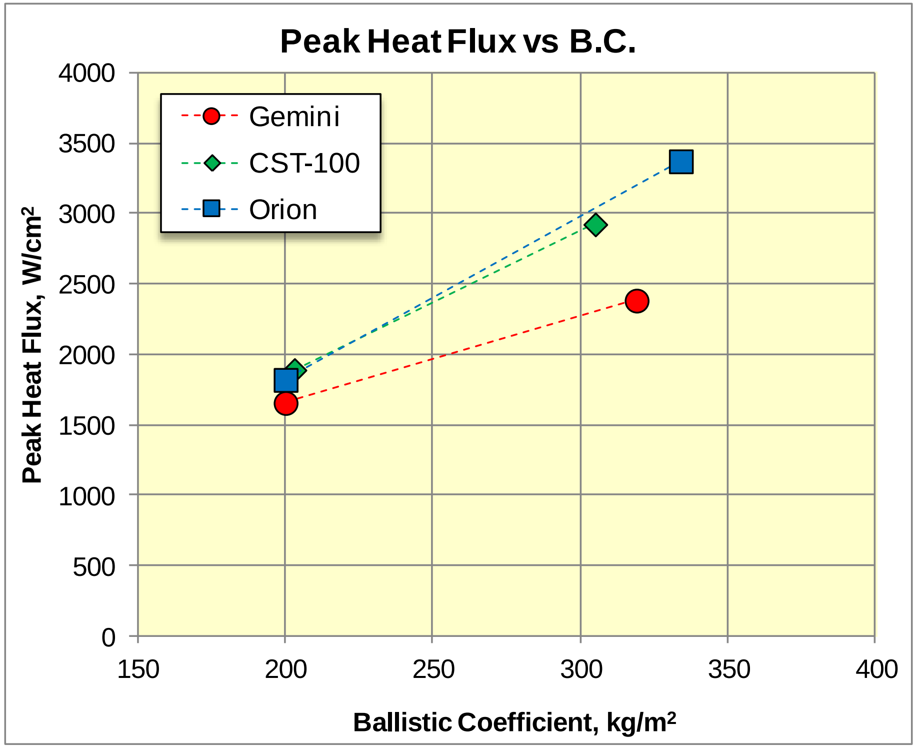
	Mass, kg	Diameter, m	B.C. kg/m²	Relative Speed, km/s	Max. G	Peak Heat Flux, W/cm²	Heat Load, MJ/m²	Max Surface Pressure, kPa
	5400*	4.56	217	10.94	5.21	464	400	21.6
Gemini	2000	2.3	319	13.7	4.92	2383	2088	33.6
Gemini	**2000**	**2.9**	**200**	**13.7**	**5.24**	**1656**	**1340**	**22.4**
CST-100	**5000**	**4.56**	**203**	**13.7**	**5.36**	**1890**	**1360**	**23.2**
CST-100	7500	4.56	305	13.7	5.5	2924	1976	35.6
Orion	**6000**	**5.03**	**200**	**13.7**	**5.3**	**1820**	**1447**	**22.5**
Orion	10000	5.03	334	13.7	5.6	3372	2502	39.2

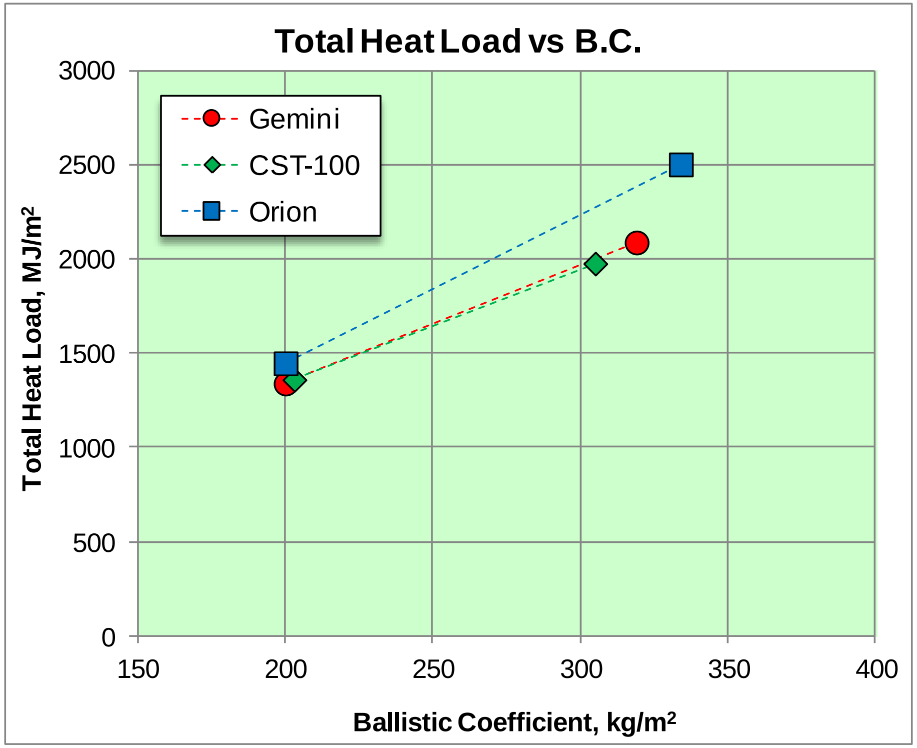
Peak heat flux and total heat load based on margin factors of 1.5 on turbulent convective heating and 2.0 on shock layer radiation heating

*** Lunar return condition, for comparison**

Effect of Ballistic Coefficient (β)

- For the 13.7 km/s reentry cases





$$\beta = \frac{4m}{C_D \pi D^2}$$

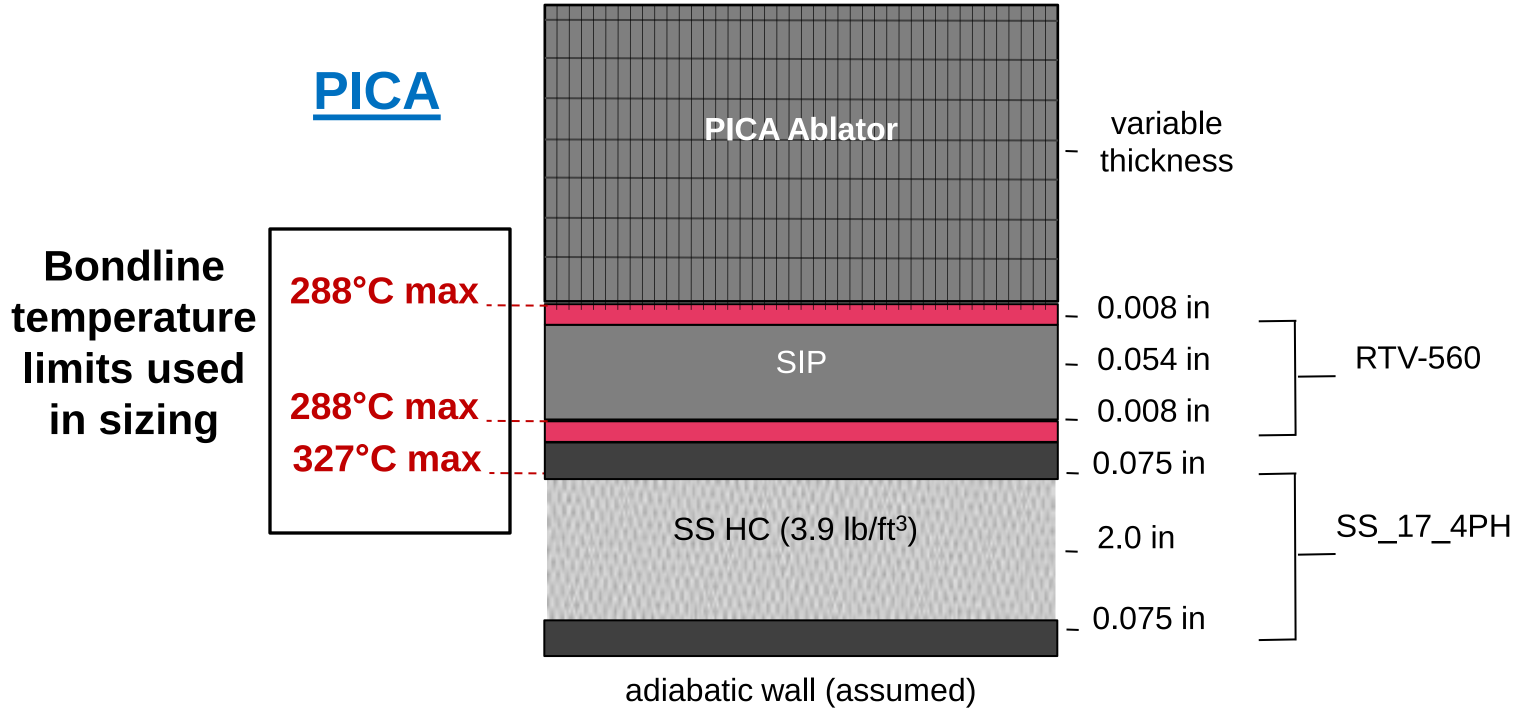
m = vehicle mass
C_D = drag coefficient
D = vehicle base diameter

TPS Sizing Process

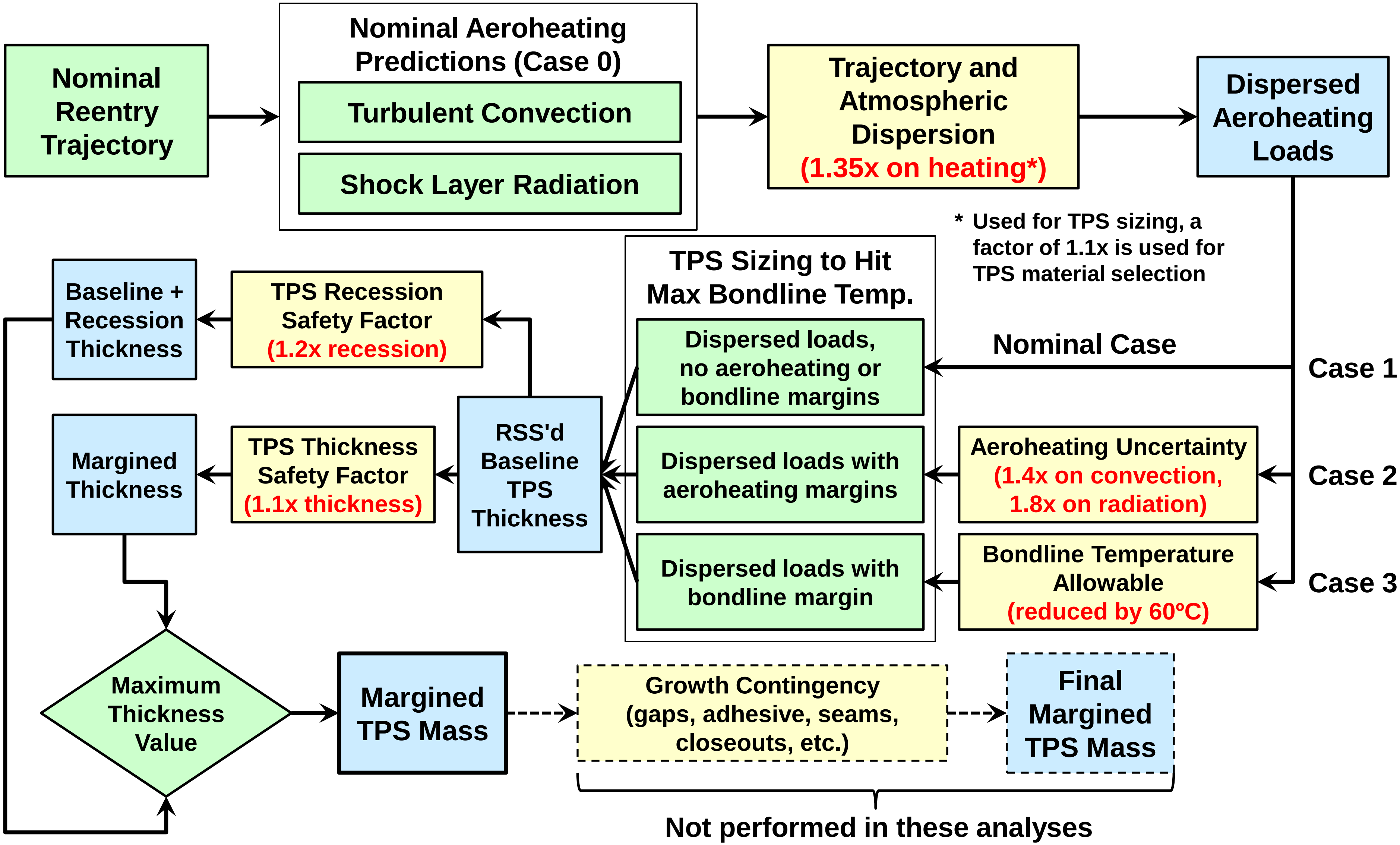
- Use aeroheating predictions to "size" the TPS for all six cases
  - Orion size vehicle at 6000 kg and 10000 kg
  - CST-100 size vehicle at 5000 kg and 7500 kg
  - Gemini size at 2000 kg, 2.3 m and 2.9 m
- Used TPSSizer tool with FIAT
- TPS: Phenolic Impregnated Carbon Ablator (PICA)
- Identical TPS layup for all cases
- Use TPS sizing margin policy, based on Orion program policy, to estimate the heatshield TPS mass

Baseline TPS Layup

- TPS material layup used in all of the sizing analyses presented here
- This layup is based on an Apollo structure and bondline, it is not necessarily representative of an actual design layup for an IM vehicle

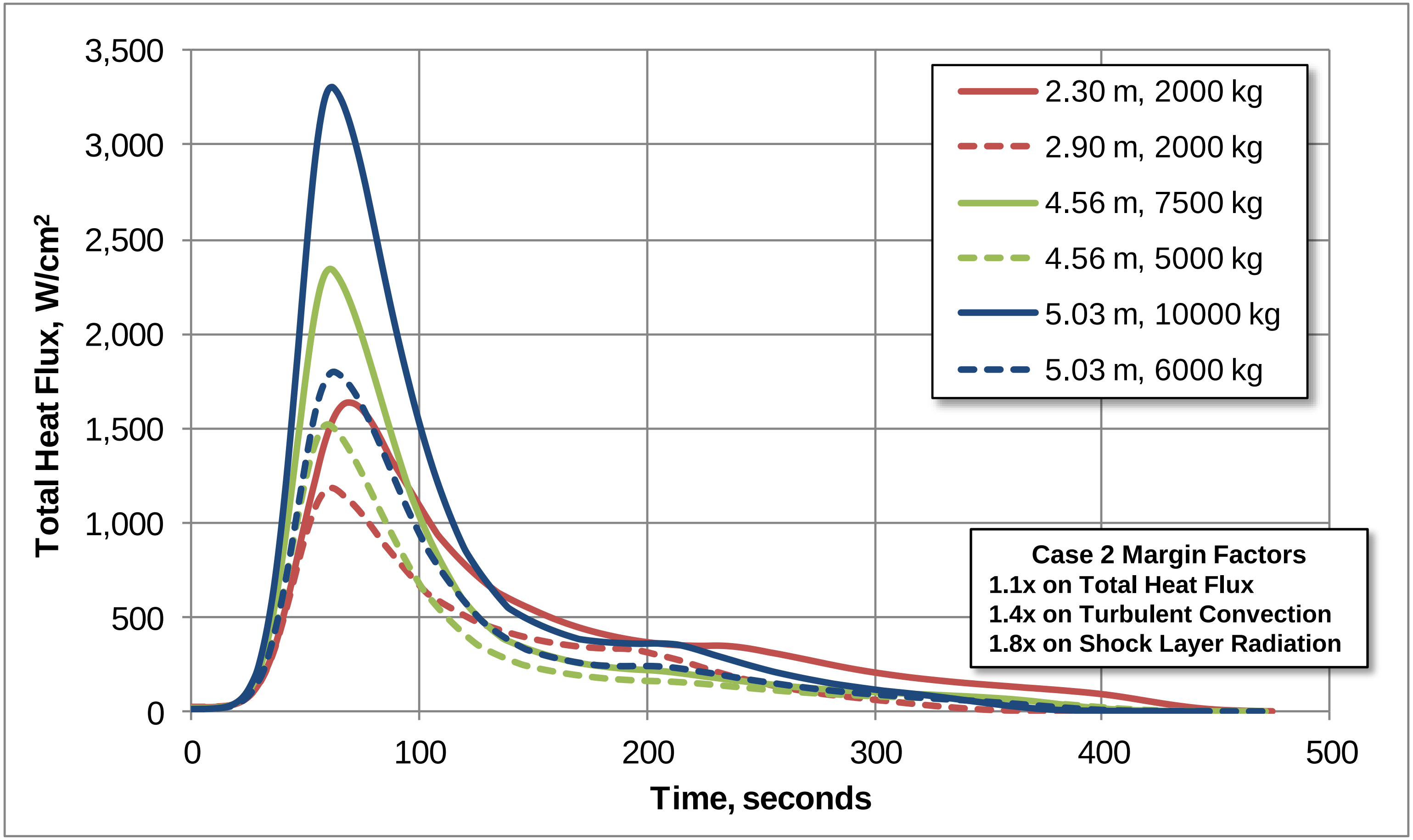


TPS Sizing Margins Policy Flowchart



Environment History – Total Aeroheating

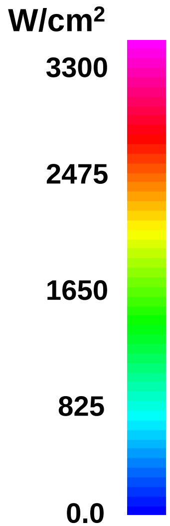
- Case 2 total aeroheating history for 13.7 km/s reentry
  - Dispersed environments plus aeroheating margin factors used for TPS material selection



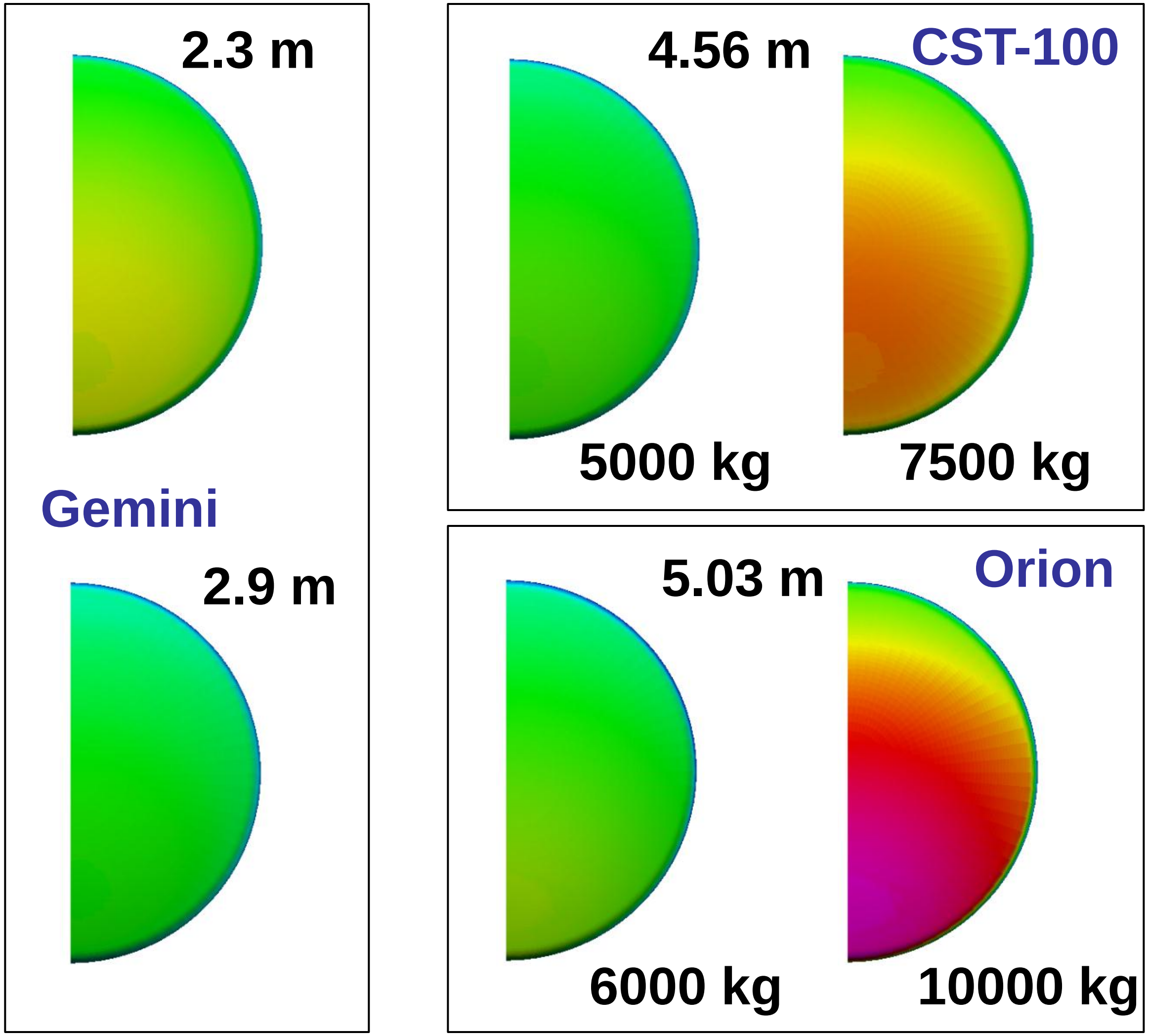
Maximum Margined Total Heat Flux

- Dispersed plus aeroheating margin factors (Case 2) for 13.7 km/s reentry

Case 2 Margin Factors
1.1x on Total Heat Flux
1.4x on Turbulent Convection
1.8x on Shock Layer Radiation



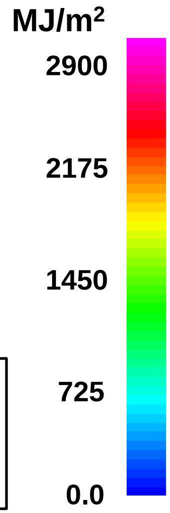
Dia., m	Mass, kg	Reentry Speed, km/s	Heat Flux, W/cm^2
2.3	2000	13.7	1952
2.9	2000	13.7	1390
4.56	5000	13.7	1544
4.56	7500	13.7	2373
5.03	6000	13.7	1778
5.03	10000	13.7	3260



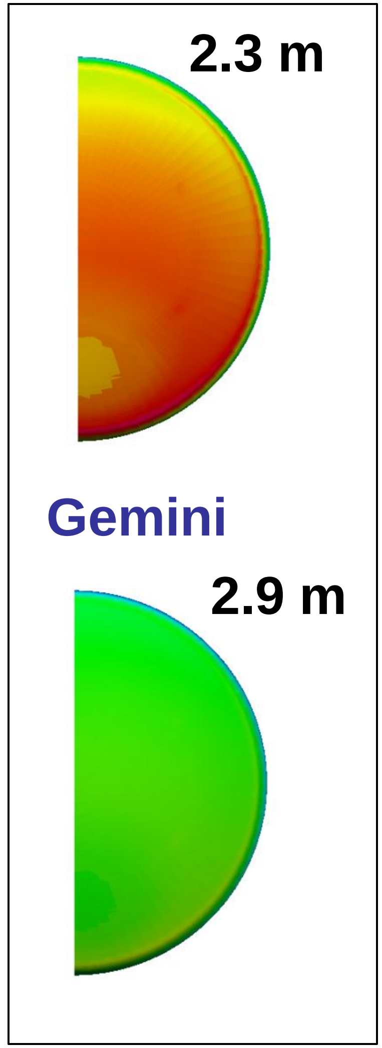
Margined Integrated Heat Load

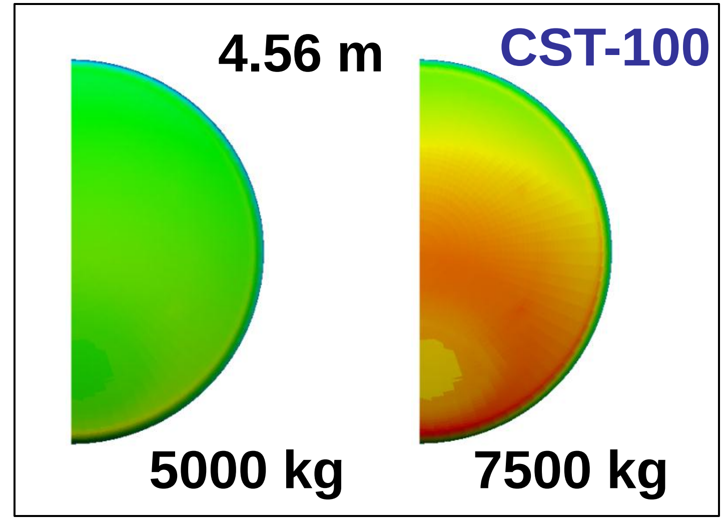
- Dispersed plus aeroheating margin factors (Case 2) for 13.7 km/s reentry

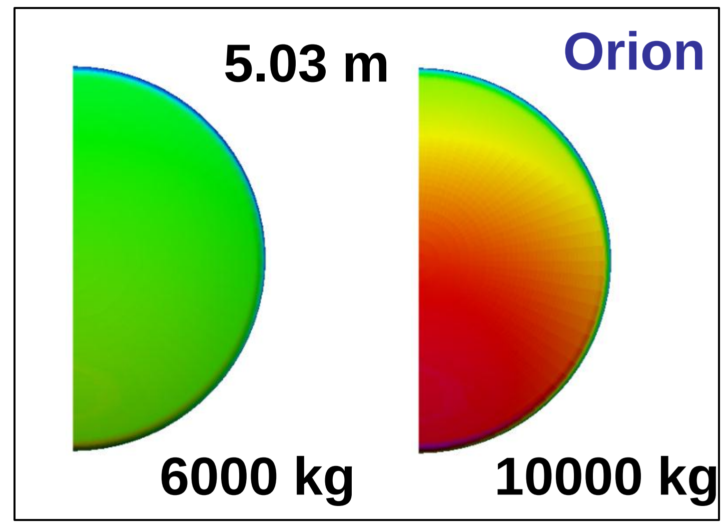
Case 2 Margin Factors
1.35x on Total Heat Flux
1.4x on Turbulent Convection
1.8x on Shock Layer Radiation



Dia., m	Mass, kg	Reentry Speed, km/s	Heat Load, MJ/m^2
2.3	2000	13.7	2531
2.9	2000	13.7	1619
4.56	5000	13.7	1660
4.56	7500	13.7	2351
5.03	6000	13.7	1749
5.03	10000	13.7	2854

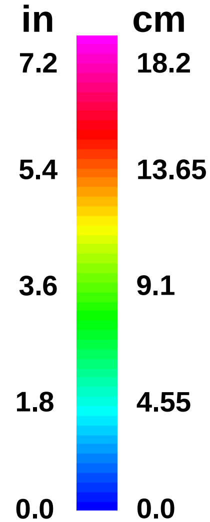


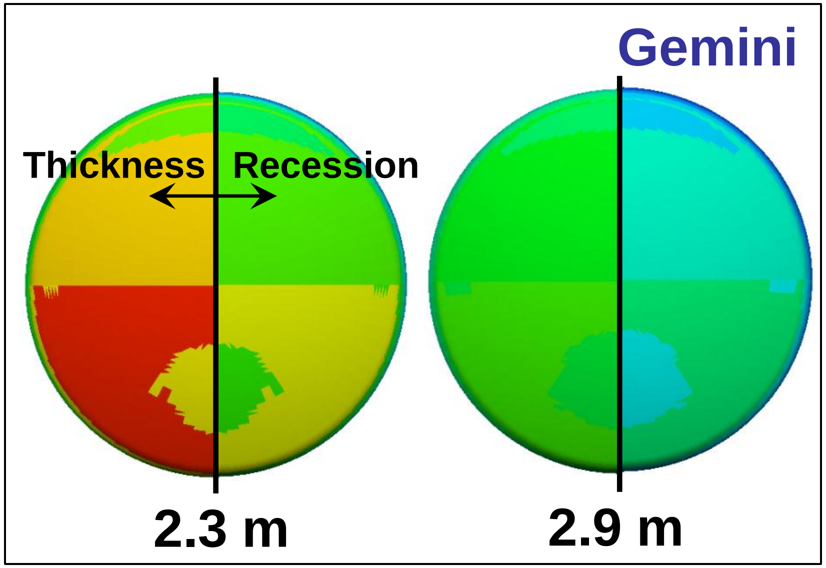


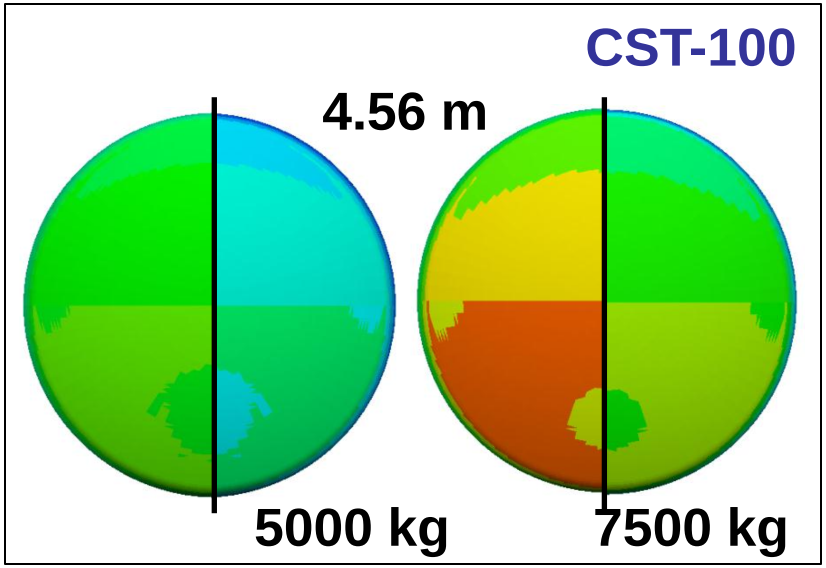


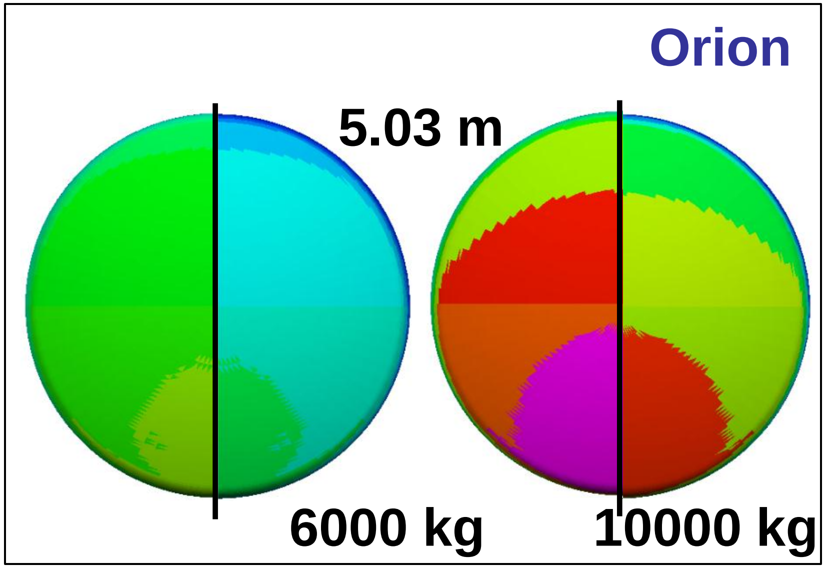
PICA RSS'd Thickness and Max Recession

Dia., m	Mass, kg	Reentry Speed, km/s	TPS Thick., cm	TPS Recess., cm
2.3	2000	13.7	14.0	10.7
2.9	2000	13.7	8.2	5.5
4.56	5000	13.7	8.7	5.7
4.56	7500	13.7	13.1	9.7
5.03	6000	13.7	9.4	6.2
5.03	10000	13.7	18.2	13.9









TPS Sizing Results Summary

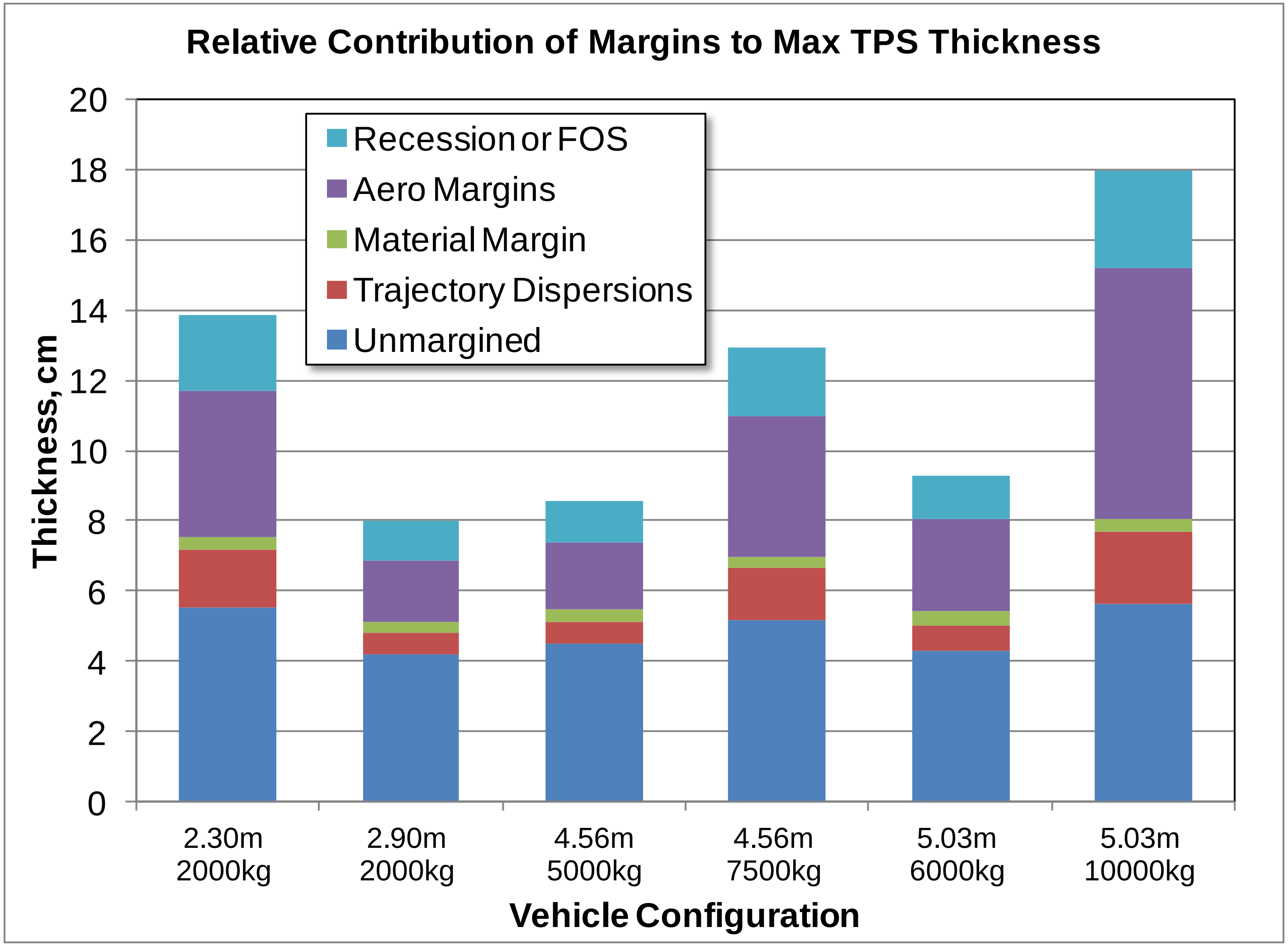
- For 13.7 km/s reentry cases

Vehicle Diameter, m	Vehicle Mass, kg	Max RSS Margined PICA Thickness, cm (in)	Max PICA Recession*, cm (in)	Total Contoured PICA Primary Heatshield Mass, kg	Total Constant Thickness PICA Primary Heatshield Mass, kg	Max Unmargined PICA Thickness, cm (in)
2.3	2000	14.0 (5.5)	10.7 (4.2)	170	229	5.55 (2.18)
2.9	**2000**	**8.2 (3.2)**	**5.5 (2.2)**	**170**	**213**	**4.18 (1.64)**
4.56	**5000**	**8.7 (3.4)**	**5.7 (2.3)**	**446**	**563**	**4.48 (1.76)**
4.56	7500	13.1 (5.2)	9.7 (3.8)	628	844	5.17 (2.04)
5.03	**6000**	**9.4 (3.7)**	**6.2 (2.4)**	**535**	**741**	**4.31 (1.70)**
5.03	10000	18.2 (7.2)	13.9 (5.5)	895	1419	5.65 (2.22)

*** Recession from margin Case 2**

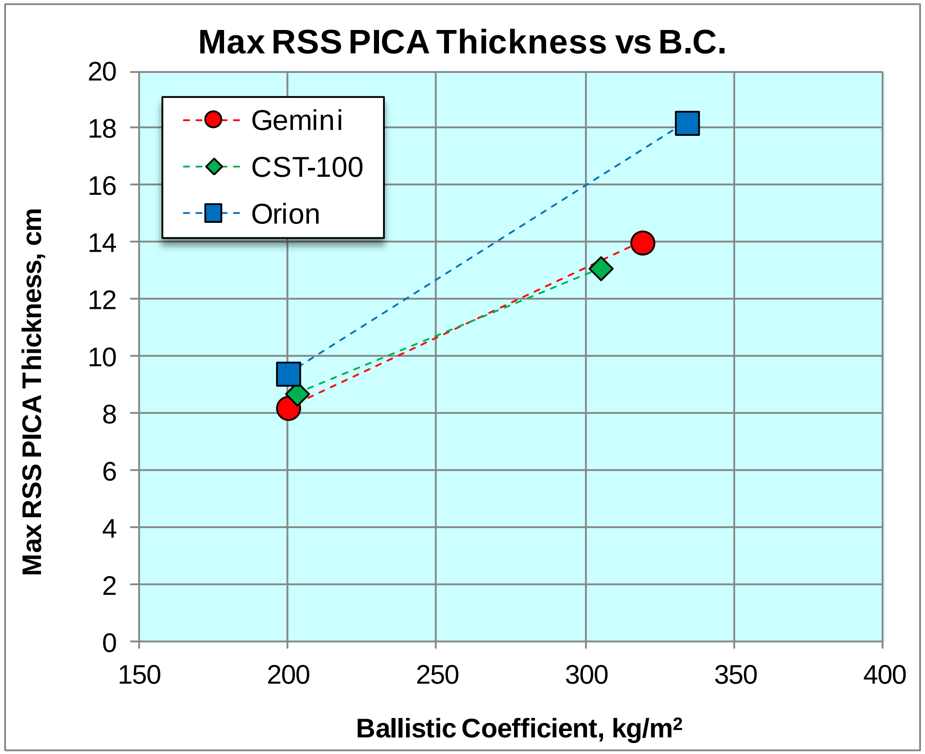
Relative Effect of Margin Parameters

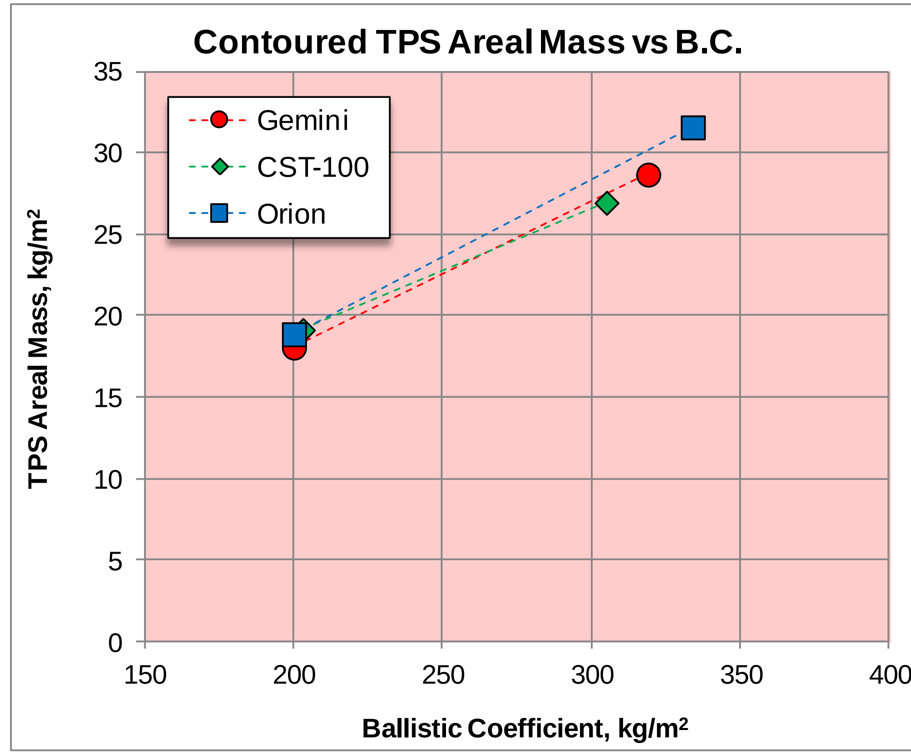
- Margins on aeroheating conditions tend to dominate



Effect of Ballistic Coefficient (β)

- For the 13.7 km/s reentry cases





$$\beta = \frac{4m}{C_D \pi D^2}$$

m = vehicle mass
C_D = drag coefficient
D = vehicle base diameter

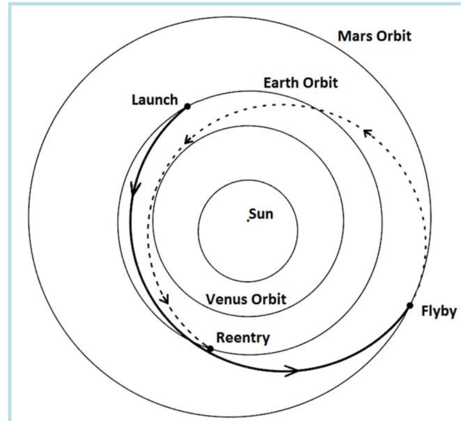
TPS Sizing Conclusions & Remarks

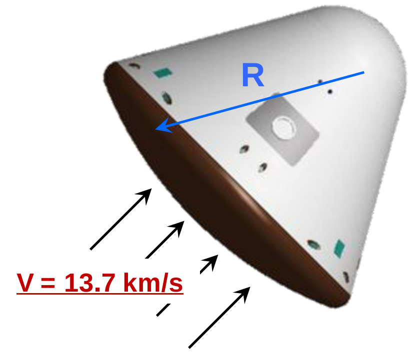
- PICA sizing analyses provides a quantitative measure of the severity of the aeroheating environments and effects of the TPS sizing margin policy
- The applied margins may be conservative, but PICA thicknesses are still within manufacturing capabilities for the vehicle cases with low ballistic coefficient (~ 200 kg/m^2)
- Large levels of recession may be an issue for aerodynamics
- Aeroheating and TPS sizing margin policy is based on lunar reentry conditions
  - Inspiration Mars may need to reevaluate the policy for their mission
- The PICA material response model has not been validated at heat flux levels beyond 1400 W/cm^2

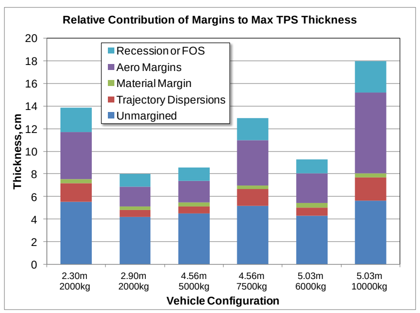
Future Work

- Analysis of Inspiration Mars reentry environments continues
  - Assessing more refined vehicle configurations and reentry conditions (latitude/longitude/direction)
  - Expanding analysis of backshell environments, TPS sizing, and mass estimates
- Investigating more detailed aspects of heatshield design and their effect on TPS mass
  - Carrier structure options
  - Gaps, bonds, seams, and penetrations
- Assessing the capabilities of ground test facilities to generate data that can help validate uncertainty and margin requirements
  - Additional testing of PICA is necessary to assess material performance and validate response models at heating rates above 1400 W/cm^2
  - Shock tube testing may be needed to anchor CFD predictions of shock layer radiation heating environments and validate aeroheating margin factors

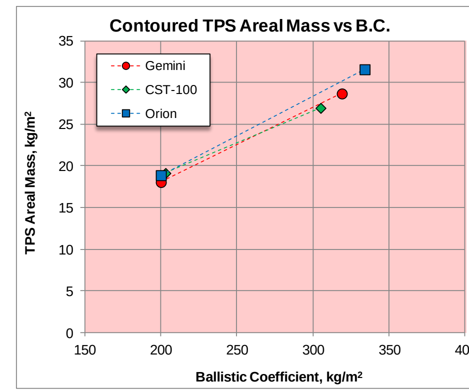
Inspiration Mars Reentry Study

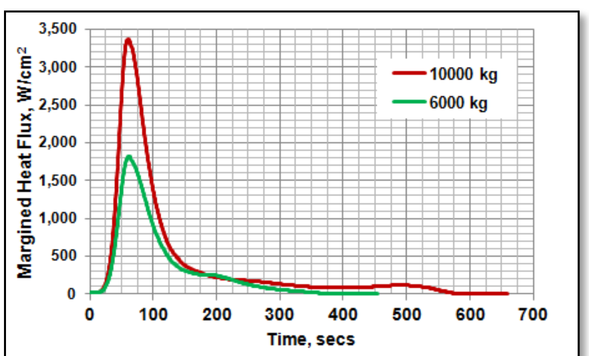


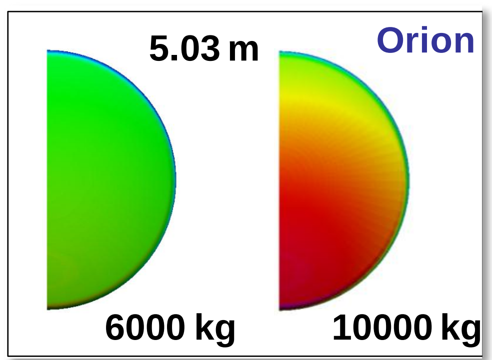


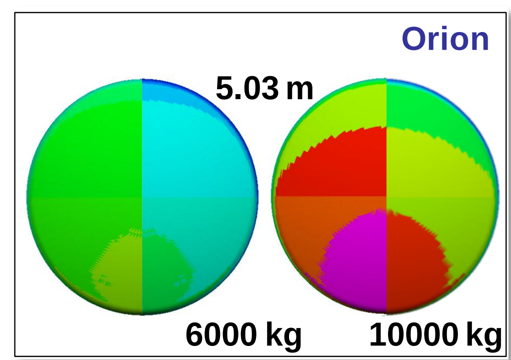


Questions?









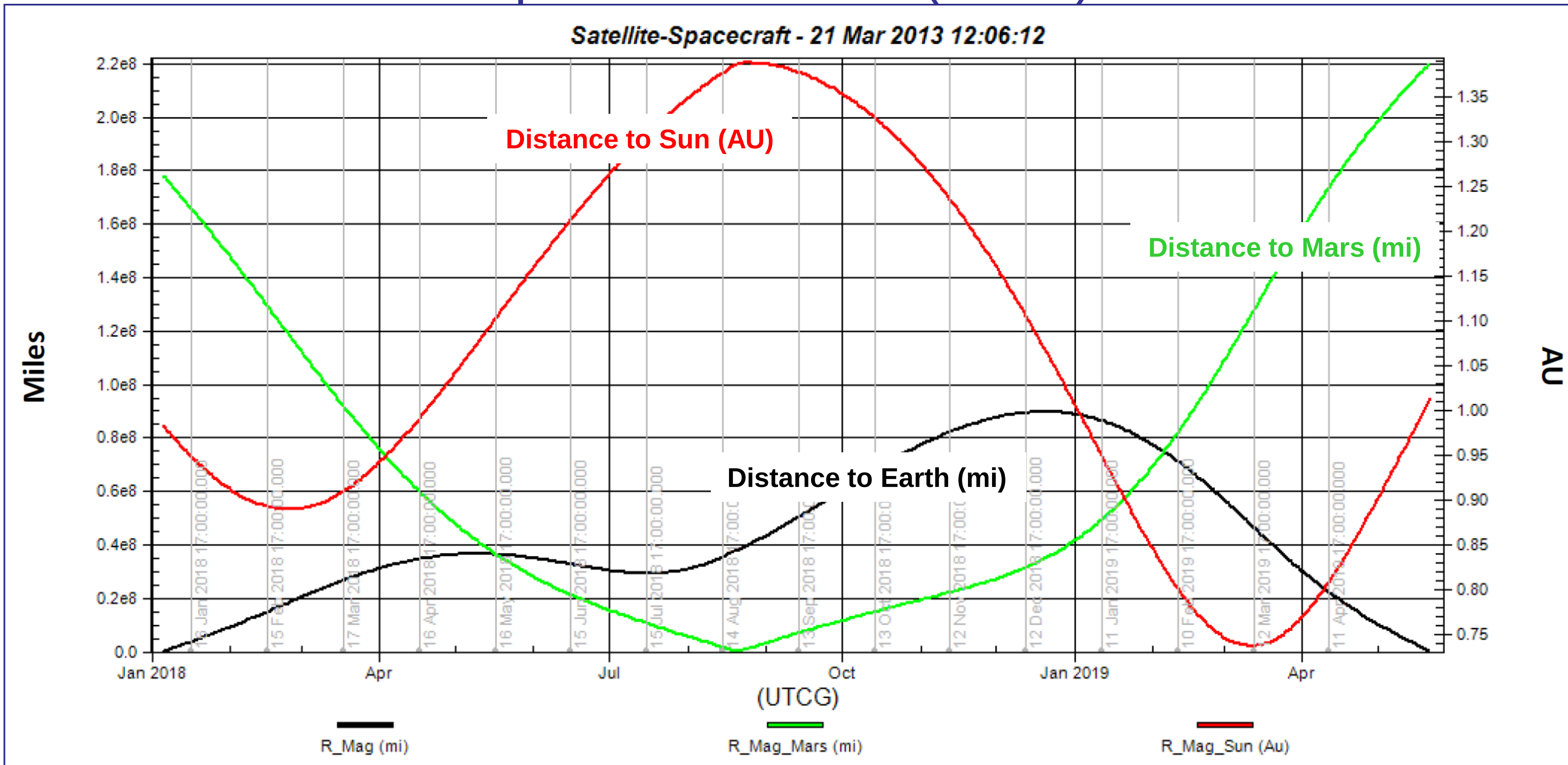
References

1. Inspiration Mars Foundation, press release, 27 Feb. 2013, http://www.inspirationmars.org.
2. M. Patel, J. Longuski, and J. Sims, "Mars Free Return Trajectories," Journal of Spacecraft and Rockets, vol. 35, no. 3, pp. 350-354, May–June, 1998.
3. D. Tito, et al., "Feasibility Analysis for a Manned Mars Free-Return Mission in 2018," IEEE Aerospace Conference 2013, Big Sky, MT, 2 March, 2013.
4. P. Desai and G. Qualls, "Stardust Entry Reconstruction," AIAA Paper 2008-1198, January, 2008.
5. POST ref
6. D. Kinney, "Aero-Thermodynamics for Conceptual Design," AIAA Paper 2004-31, January, 2004
7. D. Kinney; J. Garcia, L. Huynh, "Predicted Convective and Radiative Aerothermodynamic Environments for Various Reentry Vehicles Using CBAERO," AIAA 2006-659, January, 2006.
8. D. Kinney, "Aerothermal Anchoring of CBAERO Using High Fidelity CFD," AIAA 2007-608, January, 2007.
9. M. Wright, G. Candler, and D. Bose, "Data-Parallel Line Relaxation Method for the Navier–Stokes Equations," AIAA Journal, Vol. 36, No. 9, 1998, pp. 1603–1609.
10. M. K. McGuire, J. Bowles, L. Yang, D. Kinney, C. Roberts, "TPS Selection and Sizing Tool Implemented in and Advanced Engineering Environment," AIAA-2004-342, 42nd AIAA Aerospace Sciences Meeting and Exhibit, Reno NV, January, 2004.
11. F. Milos and Y.-K. Chen, " Ablation, Thermal Response, and Chemistry Program for Analysis of Thermal Protection Systems," AIAA Thermophysics Conference, Paper 2010-4663, June, 2010.
12. I. Cozmuta, M. Wright, B. Laub, and W. Wilcockson, "Defining Ablative Thermal Protection System Margins for Planetary Entry Vehicles," AIAA Paper 2011-3757, June, 2011.
13. A. Brandis, C. Johnston, B. Cruden, D. Prabhu, and D. Bose, "Validation of High Speed Earth Atmospheric Entry Radiative Heating from 9.5 to 15.5 km/s," AIAA Paper 2012-2865, June, 2012.
14. A. Brandis, A. Wray, Y. Liu, D. Schwenke, D. Carbon, W. Huo, C. Johnston, "Validation of HyperRad for Earth Entries," AIAA Paper 2013-2777, June, 2013.

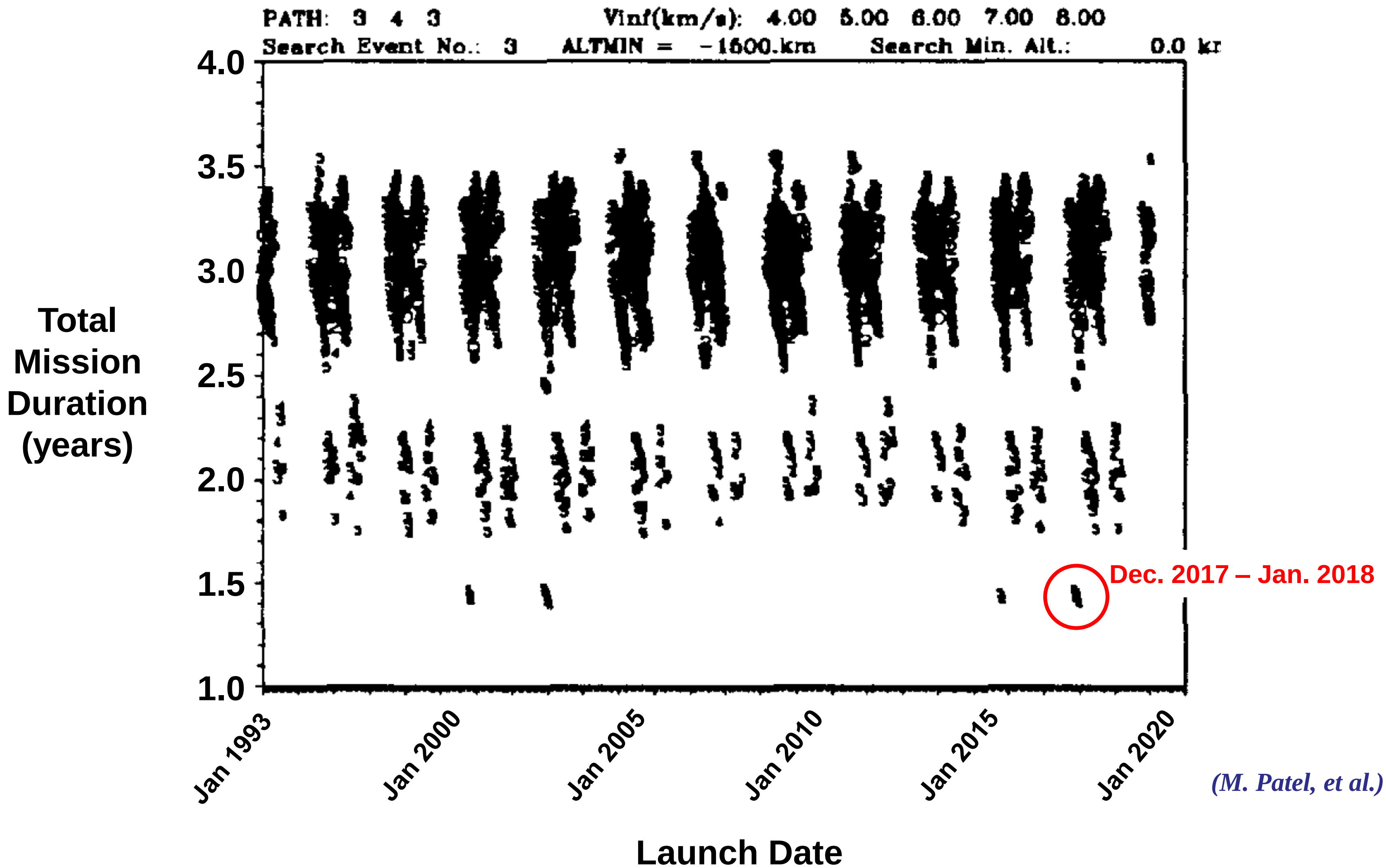
BACKUP

Trajectory Perspective

- Distance from spacecraft to Earth and Mars (in miles)
- Distance from spacecraft to Sun (in AU)



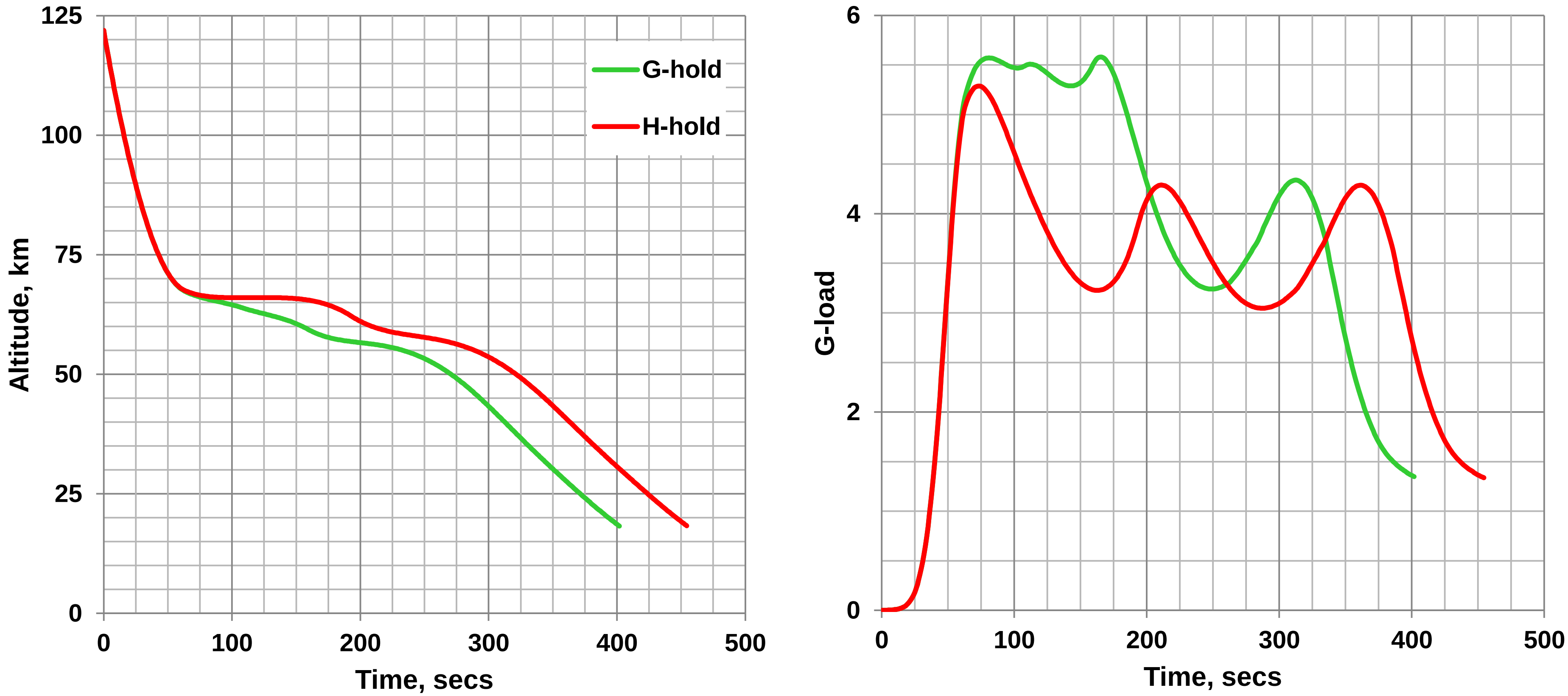
Mars Free Return Trajectory Opportunities



(M. Patel, et al.)

G-Hold/H-Hold Trajectory Comparison

- 6000 kg Orion, 13.7 km/s



Summary of Aeroheating Results

Vehicle	Mass, kg	Diameter, m	B.C. kg/m²	Relative Speed, km/s	Max. G	Peak Heat Flux, W/cm²	Heat Load, MJ/m²	Max Surface Pressure, kPa
	5400*	4.56	217	10.94	5.21	464	400	21.6
Gemini	2000	2.3	319	13.3	4.75	1981	1788	28.4
Gemini	**2000**	**2.3**	**319**	**13.7**	**4.92**	**2383**	**2088**	**33.6**
Gemini	**2000**	**2.9**	**200**	**13.7**	**5.24**	**1656**	**1340**	**22.4**
CST-100	5000	4.56	203	13.3	5.4	1686	1177	20.8
CST-100	**5000**	**4.56**	**203**	**13.7**	**5.36**	**1890**	**1360**	**23.2**
CST-100	7500	4.56	305	13.3	5.5	2620	1713	30.2
CST-100	**7500**	**4.56**	**305**	**13.7**	**5.5**	**2924**	**1976**	**35.6**
Orion	6000	5.03	200	13.3	5.5	1635	1280	21.0
Orion	**6000**	**5.03**	**200**	**13.7**	**5.3**	**1820**	**1447**	**22.5**
Orion	10000	5.03	334	13.3	5.4	2840	2058	34.4
Orion	**10000**	**5.03**	**334**	**13.7**	**5.6**	**3372**	**2502**	**39.2**

Peak heat flux and total heat load based on margin factors of 1.5 on turbulent convective heating and 2.0 on shock layer radiation heating

*** Lunar return condition, for comparison**

TPS Sizing Margin Policy Parameters

Margin Category	Value	Justification
Trajectory/Atmospheric Dispersions		
Heat Load (*used in TPS thickness predictions*)	1.35	Account for variations in total heat load due to dispersions in trajectory and atmospheric conditions
Heat Flux (*used in TPS material selection*)	1.1	Account for variations in heat flux due to dispersions in trajectory and atmospheric conditions
Pressure	1.1	Account for pressure variations in the trajectory and atmospheric conditions
Primary Heatshield Aeroheating Uncertainty		
Turbulent Convective Heating	1.4	Account for uncertainty in convective heating predictions
Shock Layer Radiation Heating	1.8	Account for uncertainty in shock layer radiation heating predictions
Backshell Heatshield Aeroheating Uncertainty		
Convective Heating	1.5	Account for uncertainty in convective heating predictions
Shock Layer Radiation Heating, when applicable	3.0	Account for uncertainty in shock layer radiation heating predictions
Bondline Condition		
Reduce Bondline Temperature Limit by…	60°C (108°F)	Account for changes in bondline allowable temperature limits
TPS Recession/Thickness		
Recession Factor of Safety	1.2	Account for uncertainty in TPS material recession predictions
Thickness Factor of Safety	1.1	Account for uncertainty in total TPS thickness predictions

Margin Case 1: Trajectory dispersion margins
Margin Case 2: Trajectory dispersions and aeroheating margins

Margined Heating/Pressure History

- Conditions at the peak heat load point for a 6000 kg Orion-sized vehicle (5.03 m diameter) at 13.7 km/s relative reentry speed
  - TPS material *selection* margins: 1.1x on total heating for dispersions, 1.4x on convective heating, and 1.8x on radiation heating