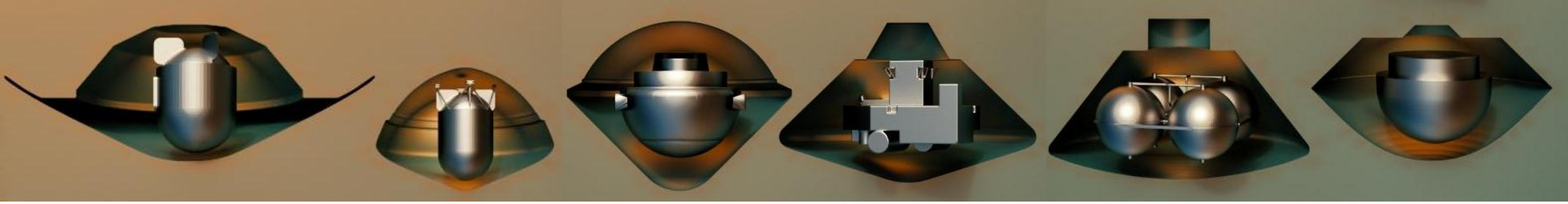


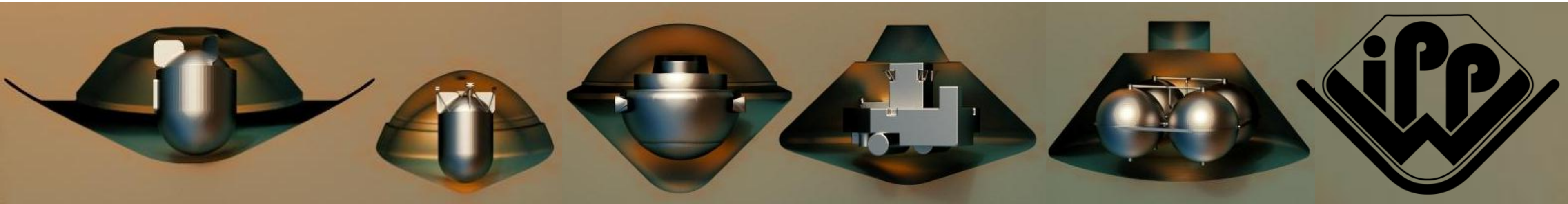
Entry, Descent, and Landing Systems Short Course

Subject: Multi-Mission System Analysis for Planetary EDL (M-SAPE)

Author: Jamshid Samareh

Systems Analysis & Concepts Directorate, NASA Langley

sponsored by
International Planetary Probe Workshop 10
June 15-16, 2013
San Jose, California



Outline

- Team Member
- Sample Return Missions
- Earth Entry Vehicle (EEV)
- M-SAPE
- Sample Results
- Summary

Additional Information will be provided on Thursday at 14:55-15:20 (8A. X-Cutting Technologies II)

Funded by NASA In-Space Propulsion Program

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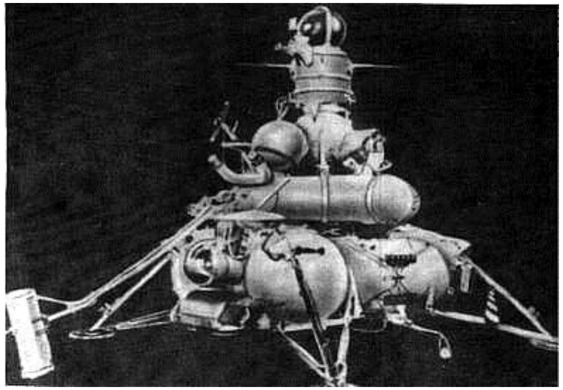
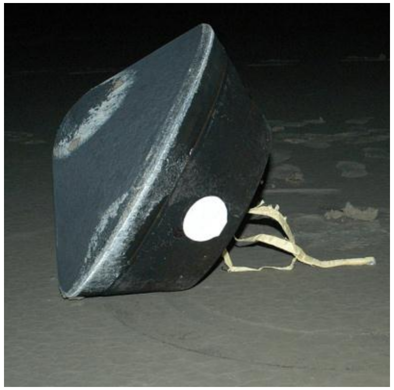
  - Kerry Zarchi (ARC)

Sample Return Missions

Luna 16, 20, 24 (1970s)



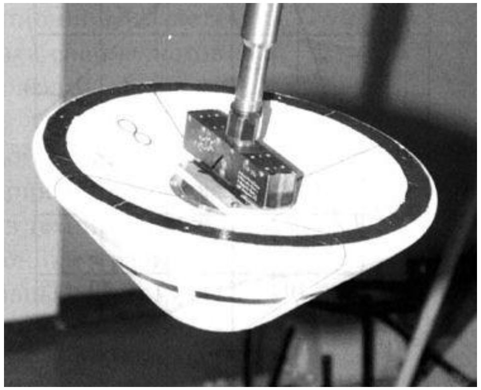
Stardust (1999-2006)



Genesis (2001-2004)

Hayabusa (2003-2010)

Fobos-Grunt (2011-2014)

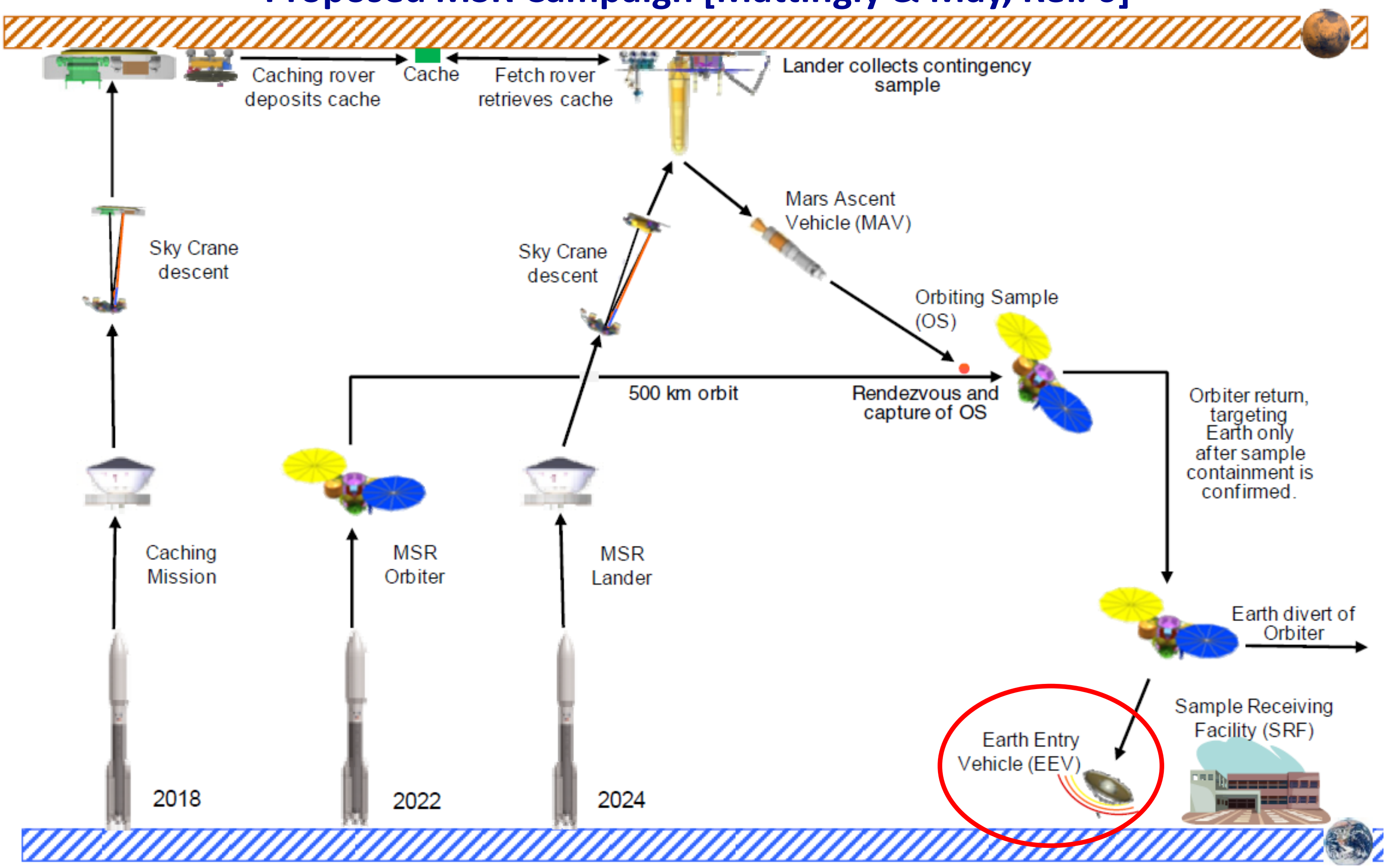


Planned Missions:

- Hayabusa 2 (asteroid)
- OSIRIS-Rex (asteroid)
- Chang'e 5 (Moon)
- MarcoPolo-R (asteroid)
- Luna-Grunt
- MSR
- Mars-Grunt
- Chinese MSR
- OpenLuna (private)

Sample Return Missions (Cont.)

Proposed MSR Campaign [Mattingly & May, Ref. 6]



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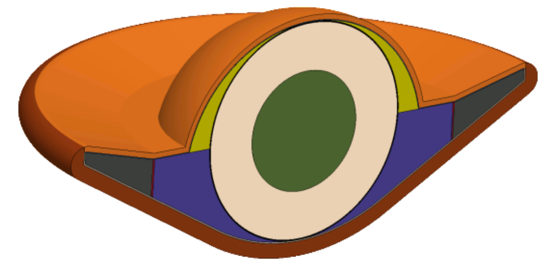
Earth Entry Vehicle (Model)

Design is based on the MSR EEV design which is driven by minimizing risk associated with sample containment (no parachute and passive aerodynamic stability).

- **By utilizing a common design concept, any sample return mission, particularly MSR, will benefit from significant risk and development cost reductions.**
- **The design provides a platform by which technologies, design elements, and materials can be flight tested prior to implementation on MSR.**



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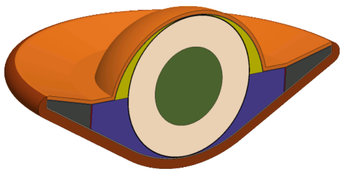
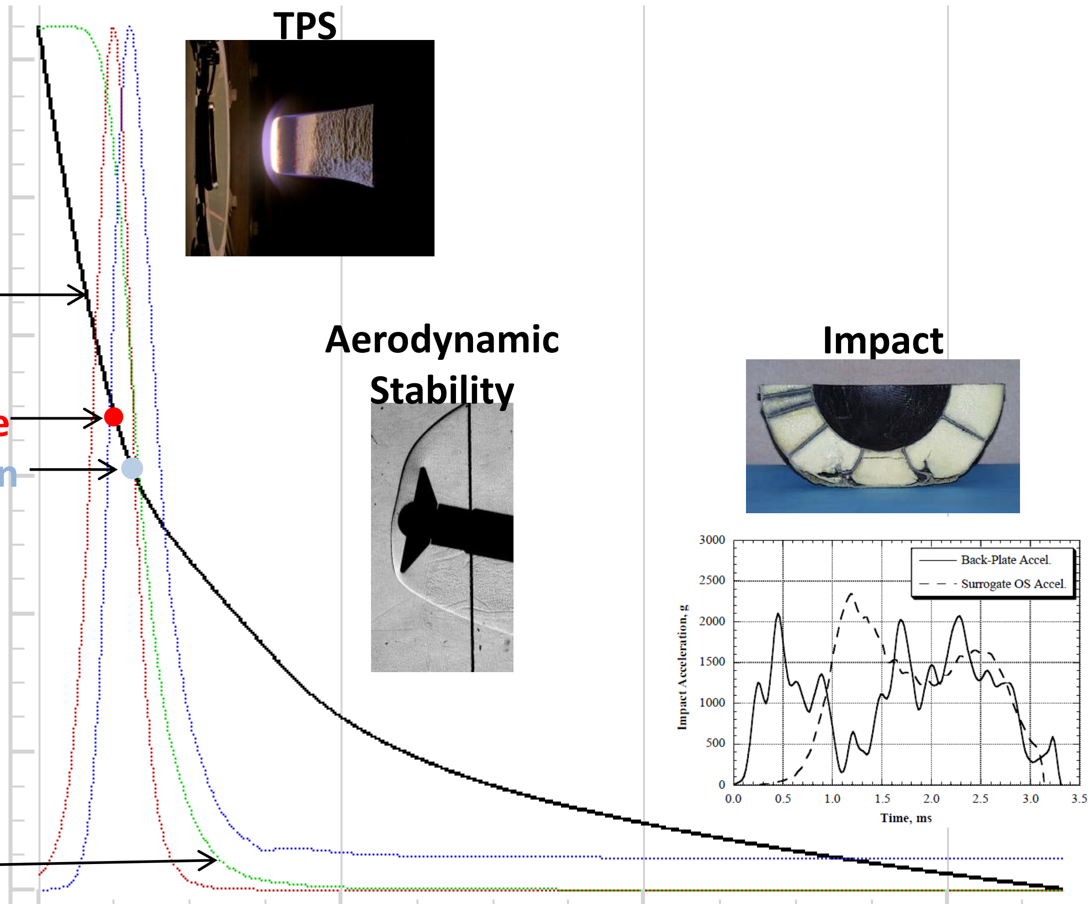
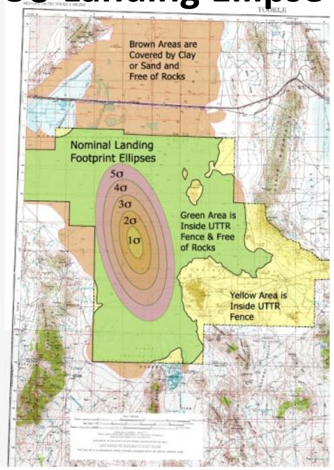
Earth Entry Vehicle (Environment)



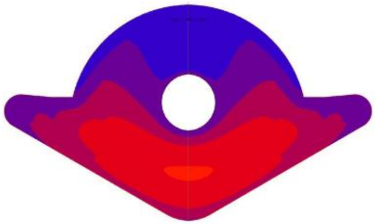
The EEV must survive extreme mechanical and thermal loads.



3σ Landing Ellipse



Thermal Soak



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M-SAPE (Design Structure Matrix)

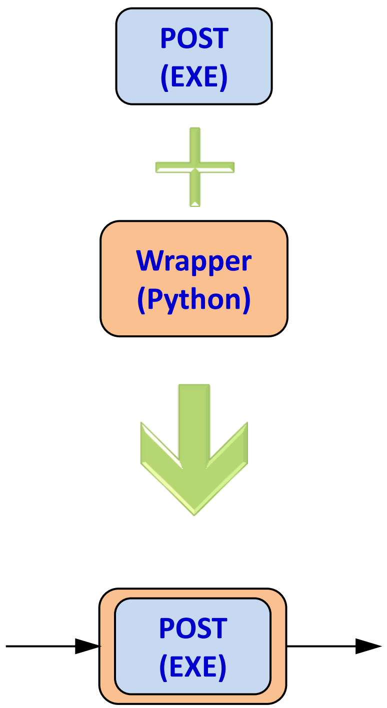
EEV design is a complex & multidisciplinary activity.

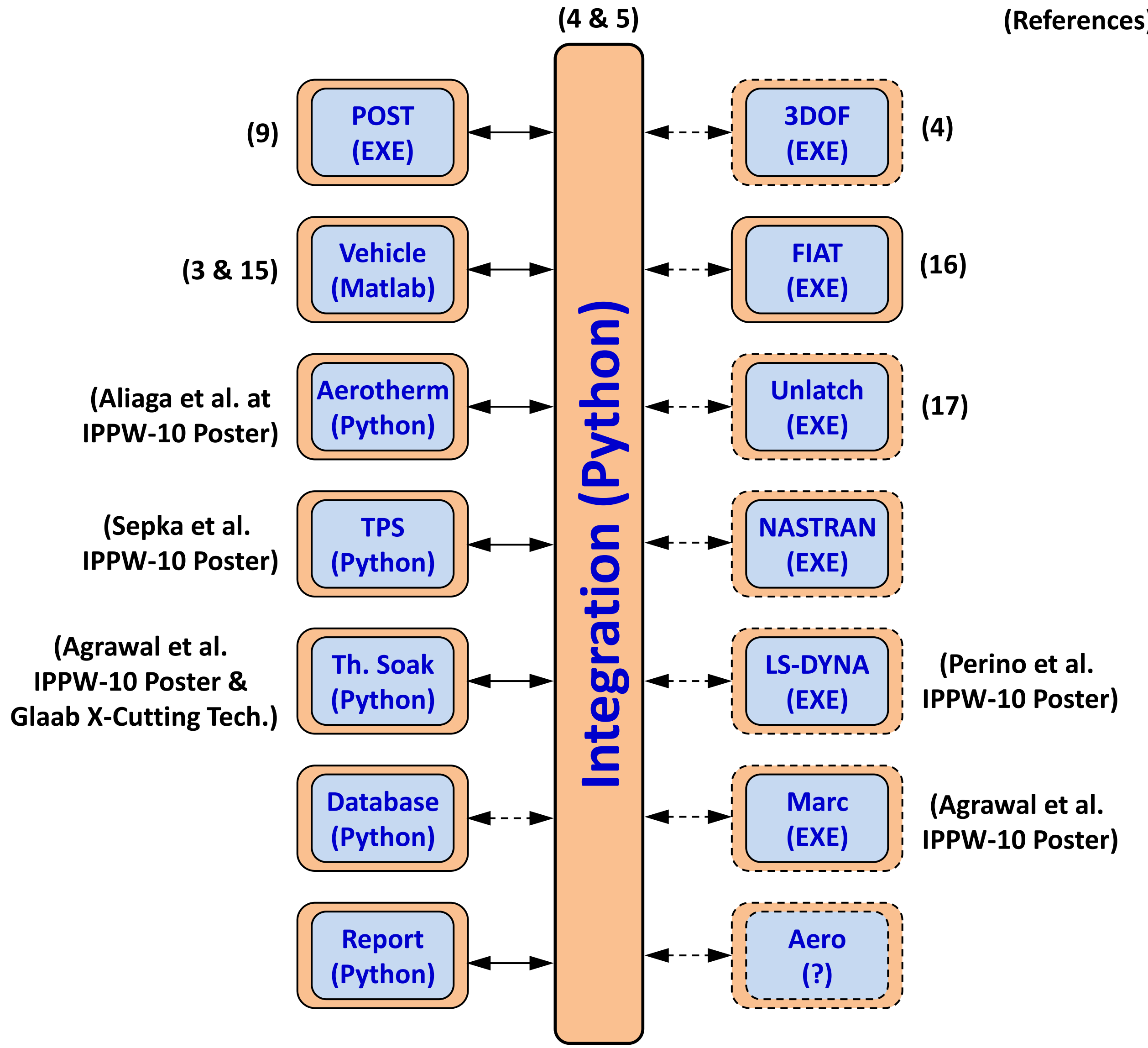
Design or Dependency Structure Matrix for MMEEV

	Database	Geometry Module	Mass Sizing & Packing	Flight Mechanics	Aerodynamics	Aerothermodynamics	TPS Sizing	Structural Analysis	Impact Analysis	Thermal Soak
Database	**Database**	Geometry Variables	Packing Arrangements	Entry Conditions						
Geometry Module	Geometry Parameters	**Geometry**	OML	OML	OML	OML	OML	OML	OML	OML
Mass Sizing	Overall Mass & Size	Overall Mass & Size	**Mass Sizing & Packing**	Mass				Mass	Mass	
Flight Mechanics	Flight Conditions			**Flight Mechanics**	Flight Conditions	Flight Conditions		Entry Loads	Terminal Velocity	
Aerodynamics	Aerodynamic Coefficients			Aerodynamic Coefficients	**Aerodynamics**			Aerodynamic Loads		
Aerothermodynamics	Thermal Constraints			Thermal Constraints		**Aerothermodynamics**	Thermal Environment		Thermal Environment	Thermal Environment
TPS Sizing	TPS Mass		TPS Mass				**TPS Sizing**	Bondline Conditions	Bondline Conditions	TPS Interface Condition
Structural Analysis	Structural Mass		Structural Mass		Aeroelastic Displacements			**Structural Analysis**		
Impact Analysis	Energy Absorber Stroke	Energy Absorber Stroke	Energy Absorber Mass						**Impact Analysis**	Impact Displacements
Thermal Soak	Thermal Soak Constraints							Temperature Field	Temperature Field	**Thermal Soak**
Approach	Flat Files & SQL	Scripts & CAD	Scripts & CAD	3DOF	Experimental Data & CFD	SG, TS, & DPLR/LAURA	FIAT	Eng. Approx. & NASTRAN	Eng. Approx. & LS-DYNA	Marc 2D-Axisymmetric

Columns are inputs, and Rows are outputs

M-SAPE (Architecture)





M-SAPE (Integration)

Integration (Python)

M-SAPE Integration [Refs. 4 & 5]:

- Uses python to automate and streamline analysis process
- Relies heavily on the object-oriented programming capabilities available in Python
- Reduces the errors resulting from manual data transfer among discipline experts
- Enables an environment that a low fidelity system analysis and trade study can be performed in hours (not days or weeks) with sufficient hooks to perform high-fidelity analysis in days.
- Uses existing software components, especially open-source software, to avoid unnecessary software development and licensing issues

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M-SAPE (Database)

Database
(Python)

Database:

- Uses flat files (CSV)
- Uses MySQL (My SQL) as a database engine.
  - The world's most widely used open source relational database management system (RDBMS).
  - Available on many platforms.
  - Used by Wikipedia, Facebook, Twitter, YouTube, …
- Uses Python interface (MySQLdb) on the front-end and PHP on the backend.
- The MySQL module has not been fully implemented yet .

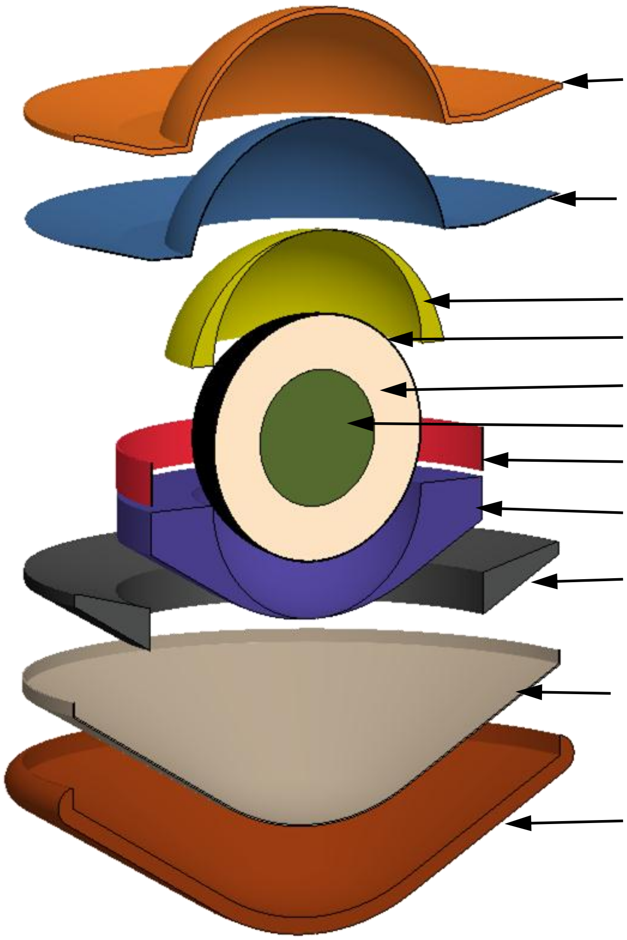
M-SAPE Disciplines (Geometry)

Vehicle (Matlab)

Geometry (Two Models):

- Simplified model (Matlab)
- CAD model developed in Pro/Engineer Wildfire 3.0
  - Constructed from a series of curves in a ”skeleton” model
  - Automated vehicle model generation
  - Generated mass properties at the component and assembly levels
  - Has two generalized configurations (MSR & Non-MSR)

MSR Concept



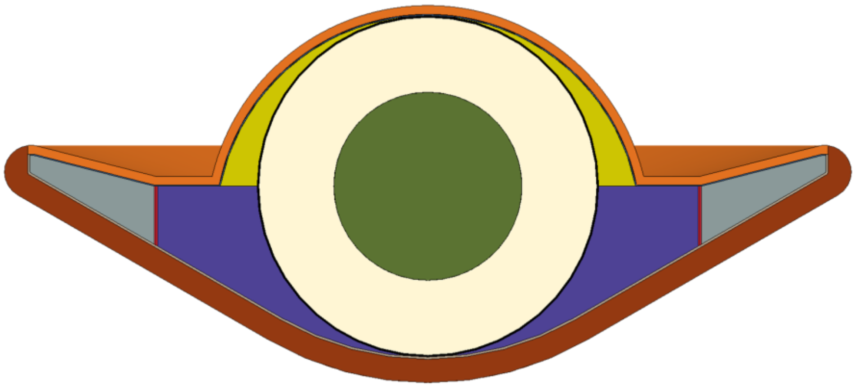
M-SAPE (Mass Sizing & Packaging)

Vehicle (Matlab)

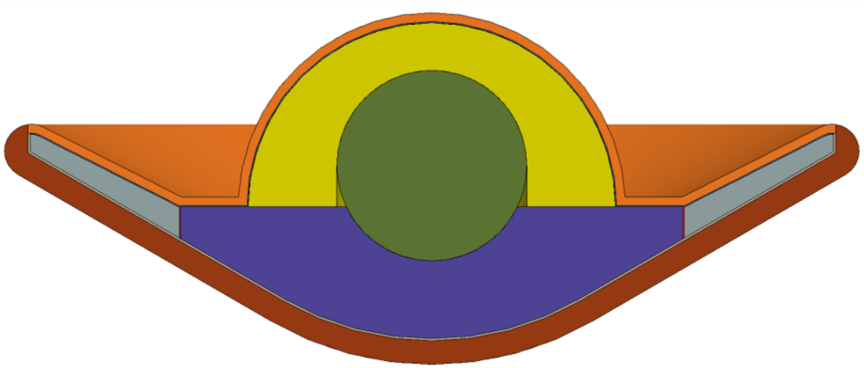
Vehicle [Refs. 4 & 5]:

- Utilizes a simplified parametric vehicle (CAD) model.
- Performs scaling by specified relationships determined through past experience, analysis, and/or mission specific requirements
- Uses MMEEV parametric model to determine the mass properties of the vehicle, across the entire vehicle trade space
- Uses a simplified 1D impact dynamics to size absorbing material.

MSR Concept



Non-MSR Concept



M-SAPE (Flight Mechanics)

POST
(EXE)

POST II [Ref. 9]:

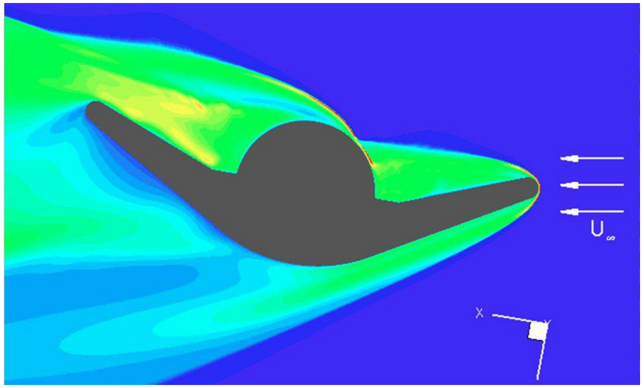
- POST II is a generalized point mass, rigid body, discrete parameter targeting and optimization trajectory simulation tool originally developed in the 1970's for Space Shuttle Program.
- It has become an industry standard and has been transferred and/or utilized by hundreds of organizations in government, industry, and academia.
- POST-II has been used for many projects (MER, Genesis, Stardust, Mars Phoenix Lander, MSL, Orion, …).
- Atmosphere Model and Winds EarthGRAM09. The planet model is an oblate planet based.
- Simulation is unguided and ballistic.

M-SAPE (Aero)

Aerodynamics [Glaab X-Cutting Tech]:

- The aerodynamics database of MMEEV uses a range of sources, including DSMC, CFD, wind tunnels and ballistics range data.
- Free-molecular static aerodynamics based on the collisionless DAC calculations.
- Hypersonic static aerodynamics are computed using LAURA code with the perfect gas air model.
- Low supersonic and high subsonic static aerodynamics were measured in the Ames 2x2 ft transonic wind tunnel by W. Marco.
- Transonic and supersonic dynamics from Viking Project.
- Low subsonic statics and dynamics obtained at NASA Langley in the Vertical Spin tunnel (VST) by Mitcheltree.

Aerodynamics at Off-Nominal Attitude



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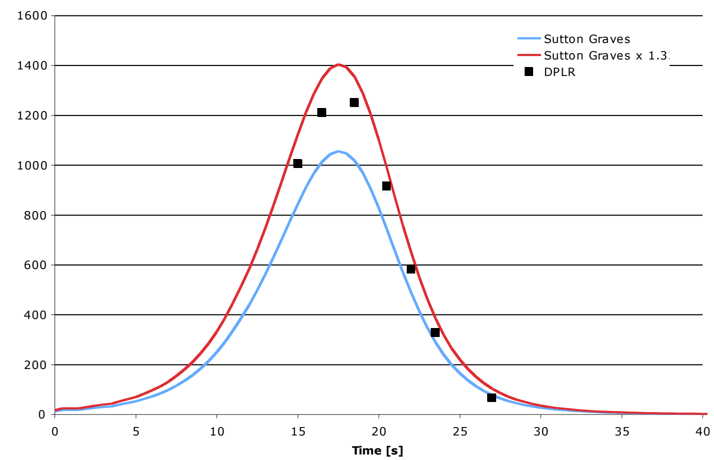
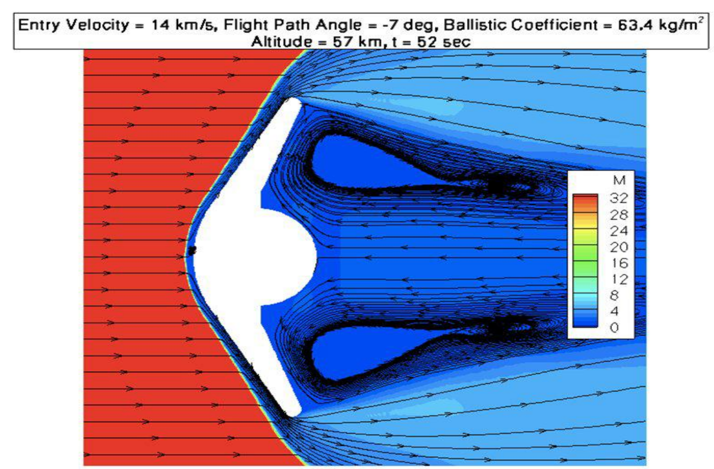
M-SAPE (Aerothermodynamics)

Aerothem (Python)

Aerothermodynamics: (Aliaga et al. At IPPW-10 Poster)

- Convective heating is based Sutton-Graves [Ref. 10] equations that has been anchored with CFD solutions (DPLR, Data Parallel Line Relaxation). The correction factor was found to be 1.33 [Ref. 11].
- Radiative heating is based on Tauber-Sutton model [Ref. 12] with no margin.





M-SAPE (TPS)

TPS
(Python)

Thermal Protection System [Refs. 13, 16 & Sepka et al. IPPW-10 Poster]:

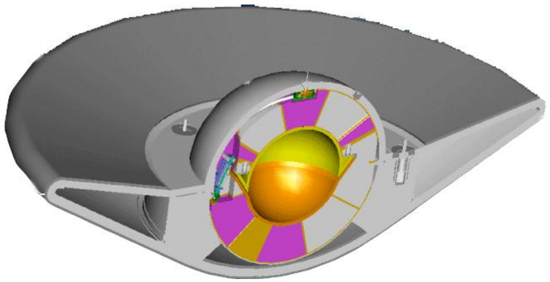
- An engineering approach which is CFD anchored was used to quickly characterize aerothermodynamic quantities pertinent to TPS design such as heat flux, heat load, and surface pressure.
- The MMEEV aeroheating environment was estimated across the entire mission and vehicle trade space. 840 trajectories total – of these approximately 120 trajectories had no recession and were not used as part of the correlation
- Correlation developed for TPS thickness based on FIAT modeling of TPS response at the forebody stagnation point.
- Constraints of an adiabatic back wall and maximum back wall temperature of 250°C.
- Available MERs are Phenolic Impregnated Carbon Ablator (PICA) and Carbon Phenolic (CP) atop Advanced Carbon-Carbon for heatshield, and Silicone Impregnated Reusable Ceramic Ablator (SIRCA), Acusil II, SLA-561V, and LI-900 for the backshell.

M-SAPE (Impact Model)

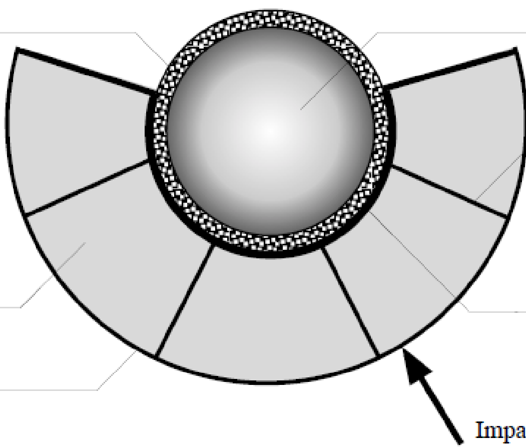
Impact (Matlab)

Simplified Impact Model [Ref. 8]:

- Crushable foam-filled cellular structure
- Crushing load is primary controlled by cell wall thickness & foam strength
- Rigid inner shell provides load reaction while protecting OS from stress concentration by cell walls
- Outer shell is designed for penetration resistance and load distribution
- Foam will also provides thermal insulation



Kellas [Ref. 8]



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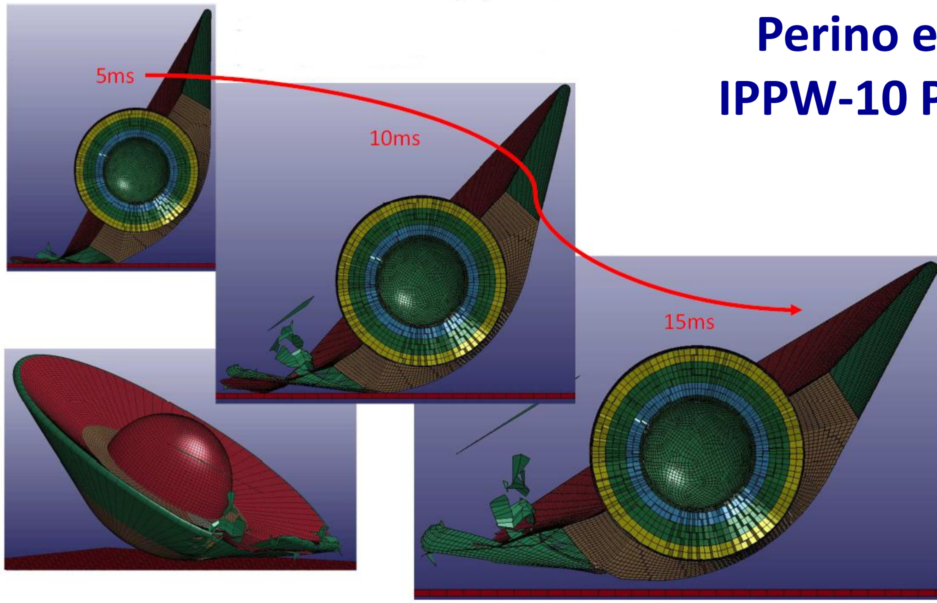
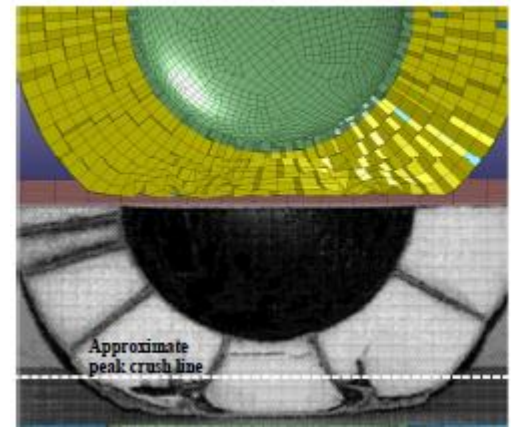
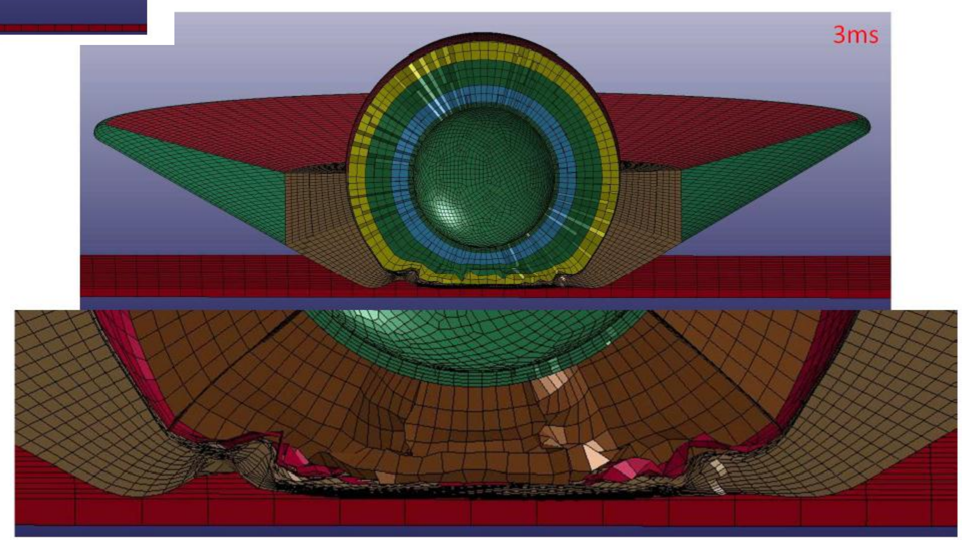
M-SAPE (Impact Model)

LSDYNA
(EXE)

Perino et al.
IPPW-10 Poster





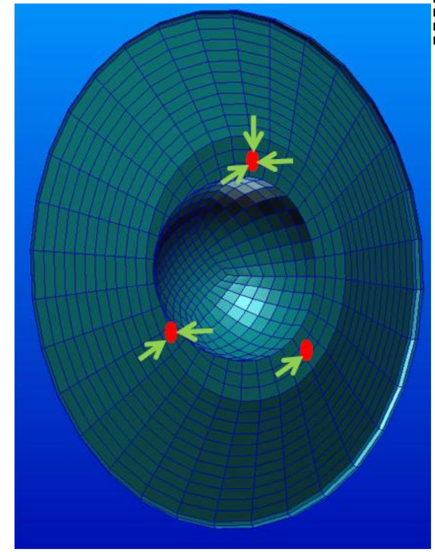


M-SAPE (Structural Sizing)

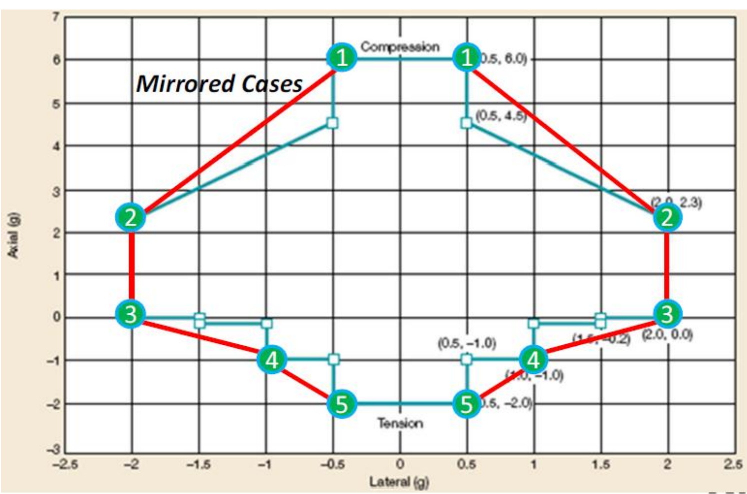
NASTRAN (EXE)

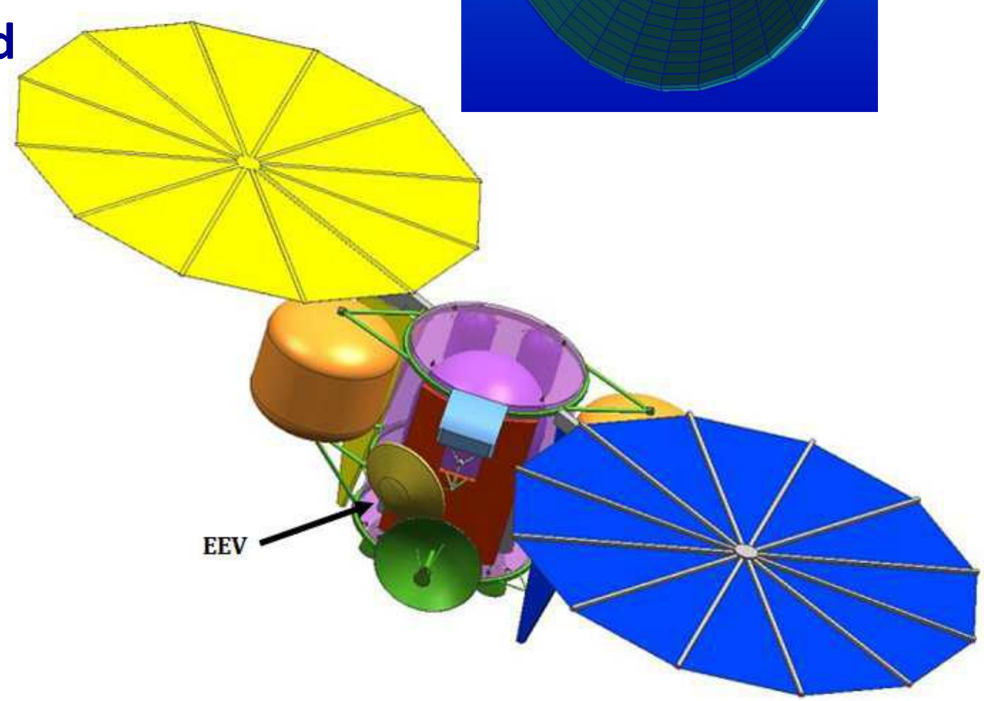
Structural Sizing Loads:

- Inertial Launch Loading
- Structure Born Vibration Load
- Random Acoustic Launch
- Inertial Reentry
- Module not fully implemented



Perino et al.
IPPW-10 Poster





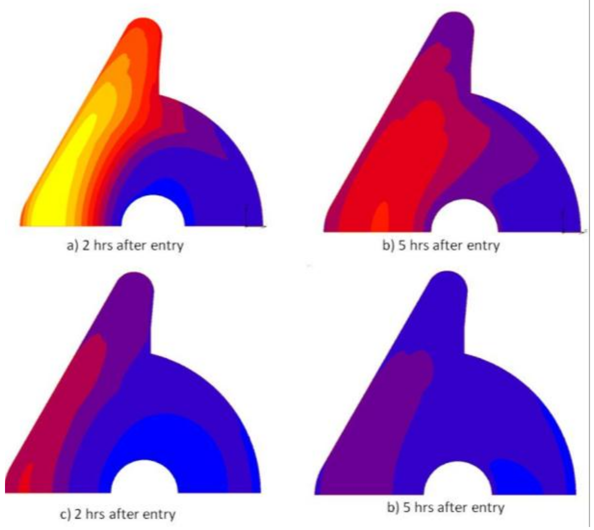
M-SAPE (Thermal Soak)

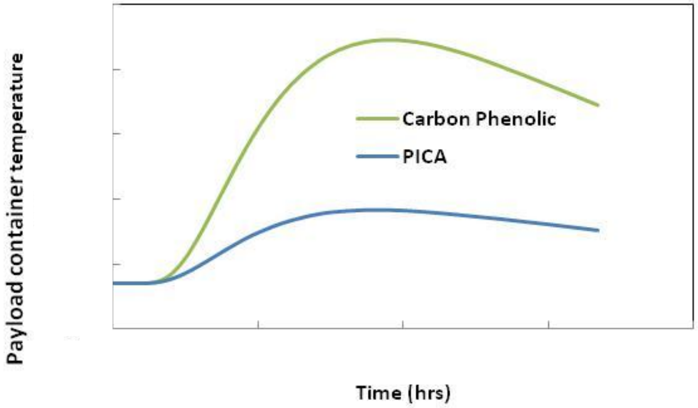
Th. Soak (Python)

Thermal Soak [Ref. 14, , Agrawal et al. IPPW-10 Poster & Glaab X-Cutting Tech]:

- Vehicle is subjected to severe thermal load.
- The survival of the entry vehicle and successful payload recovery are key to the success of sample return missions.
- Thermal soak analysis becomes very important to predict the survivability of the payload as the recovery process could take several hours.
- The commercial package, Marc-Mentat, was used to analyze thermal soak behavior
- The FE model was created based on a simplified MMEEV geometry and assumed to be 2-D axi-symmetric.

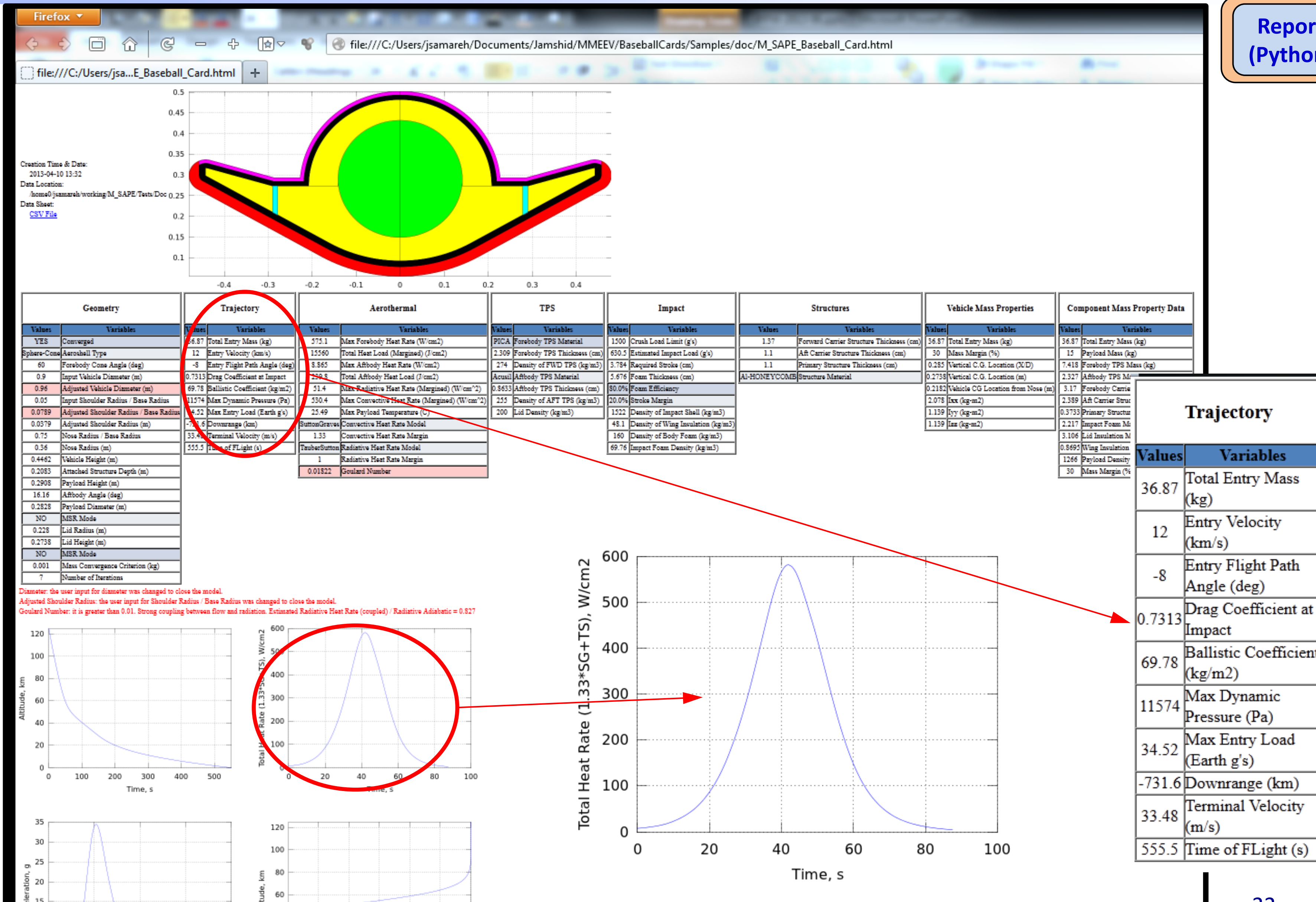
Sample Thermal Soak Results





M-SAPE (Report)

Report (Python)



Sample Results

Design or Dependency Structure Matrix for MMEEV

	Database	Geometry Module	Mass Sizing & Packing	Flight Mechanics	Aerodynamics	Aerothermodynamics	TPS Sizing	Structural Analysis	Impact Analysis	Thermal Soak
Database	**Database**	Geometry Variables	Packing Arrangements	Entry Conditions						
Geometry Module	Geometry Parameters	**Geometry**	OML	OML	OML	OML	OML	OML	OML	OML
Mass Sizing	Overall Mass & Size	Overall Mass & Size	**Mass Sizing & Packing**	Mass				Mass	Mass	
Flight Mechanics	Flight Conditions			**Flight Mechanics**	Flight Conditions	Flight Conditions		Entry Loads	Terminal Velocity	
Aerodynamics	Aerodynamic Coefficients			Aerodynamic Coefficients	**Aerodynamics**			Aerodynamic Loads		
Aerothermodynamics	Thermal Constraints			Thermal Constraints		**Aerothermodynamics**	Thermal Environment		Thermal Environment	Thermal Environment
TPS Sizing	TPS Mass		TPS Mass				**TPS Sizing**	Bondline Conditions	Bondline Conditions	TPS Interface Condition
Structural Analysis	Structural Mass		Structural Mass		Aeroelastic Displacements			**Structural Analysis**		
Impact Analysis	Energy Absorber Stroke	Energy Absorber Stroke	Energy Absorber Mass						**Impact Analysis**	Impact Displacements
Thermal Soak	Thermal Soak Constraints							Temperature Field	Temperature Field	**Thermal Soak**
Approach	Flat Files & SQL	Scripts & CAD	Scripts & CAD	3DOF	Experimental Data & CFD	SG, TS, & DPLR/LAURA	FIAT	Eng. Approx. & NASTRAN	Eng. Approx. & LS-DYNA	Marc 2D-Axisymmetric

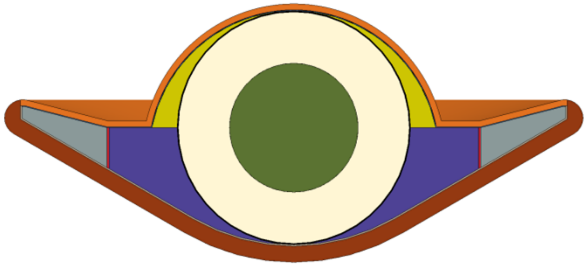
Columns are inputs, and Rows are outputs

vehicleInputParameters.csv

Payload Mass (kg)	3.6
Payload Diameter (m)	0.16
Input Vehicle Diameter (m)	0.9
Vehicle Nose Radius / Vehicle Base Radius	0.72222
Input Vehicle Shoulder Radius / Vehicle Base Radius	0.07
MSR Flag	Yes
Entry Velocity (m/s)	11500
Entry Flight Path Angle (deg)	-25
Convective Heat Rate Model	SuttonGraves
Convective Heat Rate Margin	1.33
Radiative Heat Rate Model	TauberSutton
Radiative Heat Rate Margin	1
Backshell TPS Type	SLA-561V
Forebody TPS Type	CP
Component Mass Margin	0.3
Mass Convergence Criterion	1.00E-03
Max Number of Iterations	20

Sample Results (MSR & Galahad)

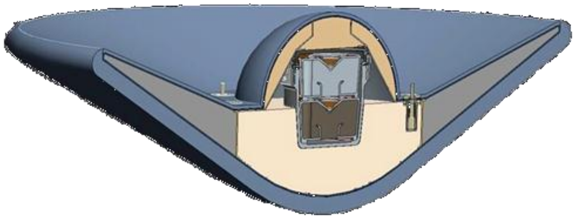
MSR



Parameters	circa 2008	M-SAPE
Diameter, m	0.9	0.9
Mass, kg	44	45.7
Entry velocity, km/s	11.56	11.5
Peak heating, w/cm2	1500*	1302
Peak deceleration g's	130	134
Terminal velocity, m/s	41	39.8

*Peak entry heating limit

Galahad



Parameters	circa 2010	M-SAPE
Total mass, kg	32.1	31.9
Maximum entry load, g's	33.9	34.7
Total peak heat rate, W/cm2	400	441
Total heat load, kJ/cm2	11.2	12.0
PICA thickness, cm	2.3	2.21
Time of flight, sec	595	673
Impact velocity, m/s	31	26.7
Impact load, g's	470	456
Impact stroke, cm	3.4	2.4

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Sample Results (Report Summary)

Adjusted Shoulder Radius (m)	Forebody TPS Mass (kg)	Max Stagnation Pressure at Density (kg/m^3)
Adjusted Shoulder Radius / Base Radius	Forebody TPS Material	Max Stagnation Pressure at Geodetic Altitude (m)
Adjusted Vehicle Diameter (m)	Forebody TPS Message	Max Stagnation Pressure at Relative Velocity (m/s)
Aeroshell Type	Forebody TPS Thickness (cm)	Max Stagnation Pressure at Time (s)
Aft Carrier Structure Mass (kg)	Forward Carrier Structure Thickness (cm)	Max Total Heat Rate (Margined) (W/cm2)
Aft Carrier Structure Thickness (cm)	Goulard Number	Max Total Heat Rate (Margined) at Density (kg/m^3)
Aft TPS Message	Impact Foam Density (kg/m3)	Max Total Heat Rate (Margined) at Geodetic Altitude (m)
Aftbody Angle (deg)	Impact Foam Mass (kg)	Max Total Heat Rate (Margined) at Relative Velocity (m/s)
Aftbody TPS Mass (kg)	Input Shoulder Radius (m)	Max Total Heat Rate (Margined) at Time (s)
Aftbody TPS Material	Input Shoulder Radius / Base Radius	Nose Radius (m)
Aftbody TPS Thickness (cm)	Input Vehicle Diameter (m)	Nose Radius / Base Radius
Attached Structure Depth (m)	Ixx (kg-m2)	Number of Iterations
Ballistic Coefficient (kg/m2)	Iyy (kg-m2)	Payload Density (kg/m3)
Convective Heat Load (Margined) (J/cm^2)	Izz (kg-m2)	Payload Diameter (m)
Convective Heat Rate Margin	Lid Density (kg/m3)	Payload Height (m)
Convective Heat Rate Model	Lid Height (m)	Payload Mass (kg)
Converged	Lid Insulation Mass (kg)	Primary Structure Mass (kg)
Crush Load Limit (g's)	Lid Radius (m)	Primary Structure Thickness (cm)
Date and Time	MSR Mode	Radiative Heat Load (Margined) (J/cm^2)
Density of AFT Carrier Structure (kg/m3)	Mass Convergence Criterion (kg)	Radiative Heat Rate (coupled) / Radiative Adiabatic
Density of AFT TPS (kg/m3)	Mass Margin (%)	Radiative Heat Rate Margin
Density of Body Foam (kg/m3)	Max Aftbody Heat Rate (W/cm2)	Radiative Heat Rate Model
Density of FWD Carrier Structure (kg/m3)	Max Convective Heat Rate (Margined) (W/cm^2)	Required Stroke (cm)
Density of FWD TPS (kg/m3)	Max Convective Heat Rate (Margined) at Density (kg/m^3)	Run Name
Density of Impact Shell (kg/m3)	Max Convective Heat Rate (Margined) at Geodetic Altitude (m)	Stroke Margin
Density of Wing Insulation (kg/m3)	Max Convective Heat Rate (Margined) at Relative Velocity (m/s)	Structure Material
Downrange (km)	Max Convective Heat Rate (Margined) at Time (s)	Terminal Velocity (m/s)
Drag Coefficient at Impact	Max Dynamic Pressure (Pa)	Time of FLight (s)
Entry Flight Path Angle (deg)	Max Entry Load (Earth g's)	Total Aftbody Heat Load (J/cm2)
Entry Velocity (m/s)	Max Forebody Heat Rate (W/cm2)	Total Entry Mass (kg)
Estimated Impact Load (g's)	Max Payload Temperature (C)	Total Heat Load (Margined) (J/cm2)
Foam Density (kg/m3)	Max Radiative Heat Rate (Margined) (W/cm^2)	Trajectory Model
Foam Efficiency	Max Radiative Heat Rate (Margined) at Density (kg/m^3)	Vehicle CG Location from Nose (m)
Foam Thickness (cm)	Max Radiative Heat Rate (Margined) at Geodetic Altitude (m)	Vehicle Height (m)
Forebody Carrier Structure Mass (kg)	Max Radiative Heat Rate (Margined) at Relative Velocity (m/s)	Vertical C.G. Location (X/D)
Forebody Cone Angle (deg)	Max Radiative Heat Rate (Margined) at Time (s)	Vertical C.G. Location (m)
	Max Stagnation Pressure (atm)	Wing Insulation Mass (kg)

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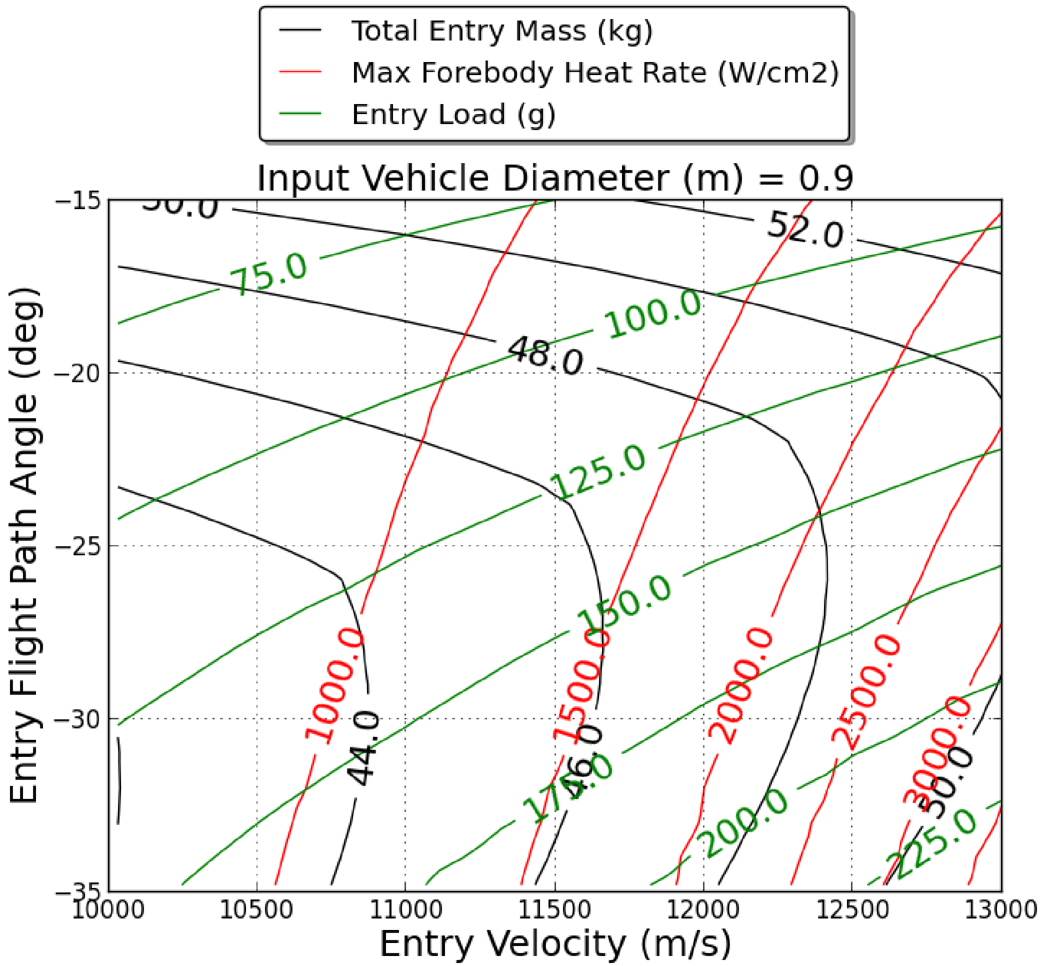
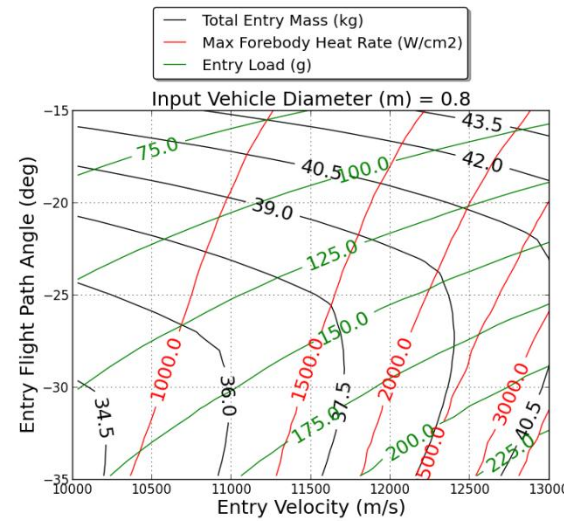
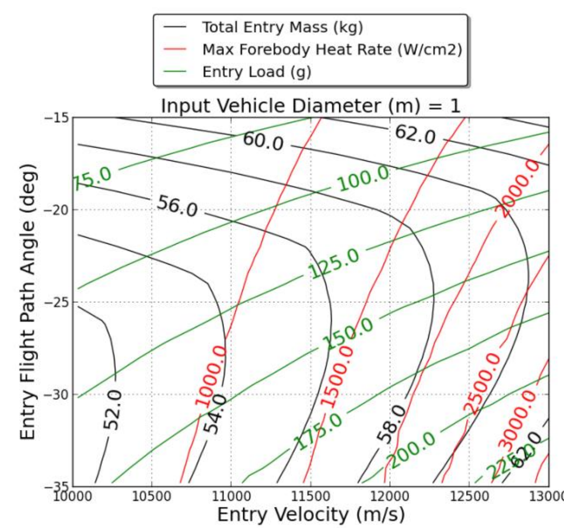
Sample Results (MSR)
(Trade Space, 2457 Runs)







Summary

- An integrated system analysis capability for Earth entry vehicle was presented.
- The model was based on MSR concept.
- The system allows:
  - Single analysis
  - What if scenarios (e.g., payload density)
  - Technology evaluation (e.g., TPS concepts & energy absorbers)
  - System sensitivity analysis
  - System trade space analysis
  - System level Monte Carlo analysis (not fully implemented yet)
- M-SAPE is still in development.
- The plan is to extend the current system for general EDL applications that include additional planets.

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