Session 8: Closing Session, Student Awards, and the Future

Overview of the NASA Entry, Descent, and Landing Systems Analysis (EDL-SA)

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Acknowledgements

- The work of the EDL-SA is carried out by more than 20 team members across NASA, from:
  - Ames Research Center
  - Johnson Space Center
  - Jet Propulsion Laboratory
  - Langley Research Center

- The team's accomplishments are documented in:
  - Year 2 Mid-Year Report: *"Entry, Descent and Landing Systems Analysis (EDL-SA) for High Mass Exploration and Science Mars Mission Systems,"* EDLSA-003, 8 March 2010*.* Document Availability Authorization: NF 1676L ID 10350, March 8, 2010
  - Year 1 NASA Technical Memorandum: "*Entry, Descent and Landing Systems Analysis Study: Phase 1 Report*" (pending release)

Mars Design Reference Architecture 5.0
Entry, Descent & Landing Recommendations

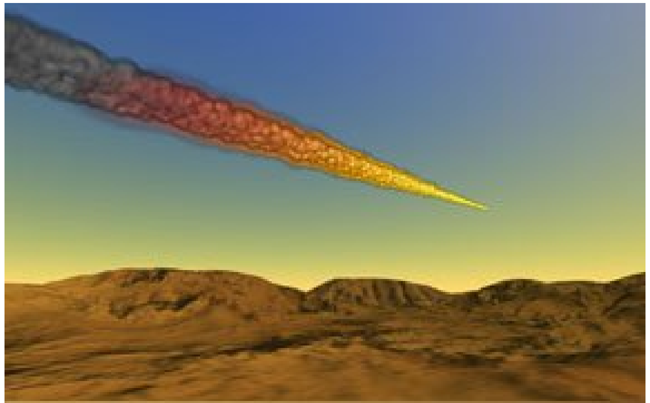
- **Aerocapture** of uncrewed cargo vehicles continues to remain the leading option for chemical propulsion architecture

- First use of **EDL identified as a key risk driver** (scalable/near-full scale precursor will help retire risk)

- Landing of large payloads (greater than 2 MT) on the surface of Mars remains a **key challenge** (How do we decelerate high ballistic coefficient vehicles?)

- **Investments** in fundamental research and system studies for EDL technologies are highly recommended

- **Thorough EDL risk mitigation strategy**, including robotic mission demonstration and use of EDL systems which are scalable/near-full scale to human mission needs is highly recommended



DRA 5.0 address: http://www.nasa.gov/exploration/library/esmd_documents.html

EDL-SA Motivation

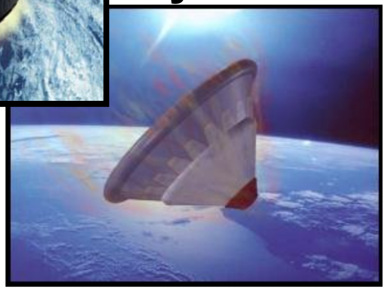
- **NASA does not have the technology in-hand to land large masses on the Mars surface.** MSL is at the upper limit of what can be done with today's Viking heritage technology.

- In May 2008 the NASA Strategic Management Council (Administrator, Mission Directors, Center Directors) commissioned the 3-year Entry, Descent and Landing Systems Analysis Study to establish **EDL technology needs based upon mission-driven requirements**

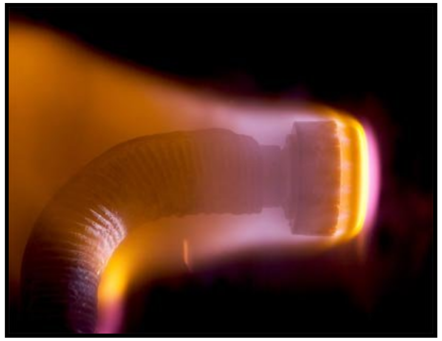
Objectives of the EDL-SA Study

- Overall Objective:
  - Develop a strategy and plan for NASA to be able to successfully land large payloads at Mars for both large robotic and Exploration-class (human) missions
- Year-by-Year Foci
  - Identify the broad areas requiring technology development for **Exploration-class missions** (Year 1 - 2009)
    - e.g., dual heat pulse-capable TPS
  - Identify the broad areas requiring technology development for **large robotic-class missions** (Year 2 - 2010)
    - e.g., inflatable decelerators
  - Develop detailed, costed, integrated (cross-cutting**) technology development plans** to TRL = 6 (Year 3 - 2011)
    - e.g., dual-layer TPS, inflatable decelerators
    - e.g., supersonic retro-propulsion, reefed parachutes

Summary of Component Technologies for Mars Aerocapture and EDL

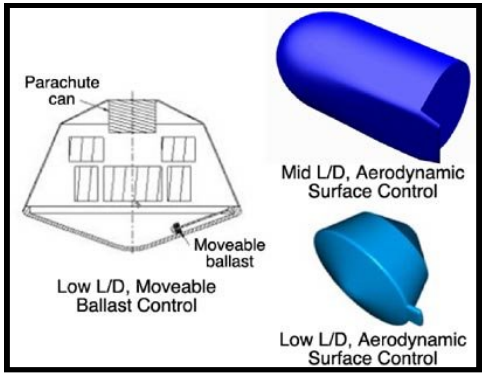



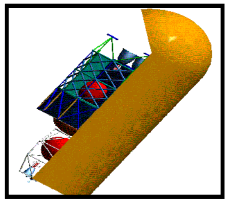
Inflatable / Deployable Decelerator Systems



Improved Lightweight, Dual-Pulse Thermal Protection System Materials

Propulsive Decelerator Options (supersonic / terminal descent)



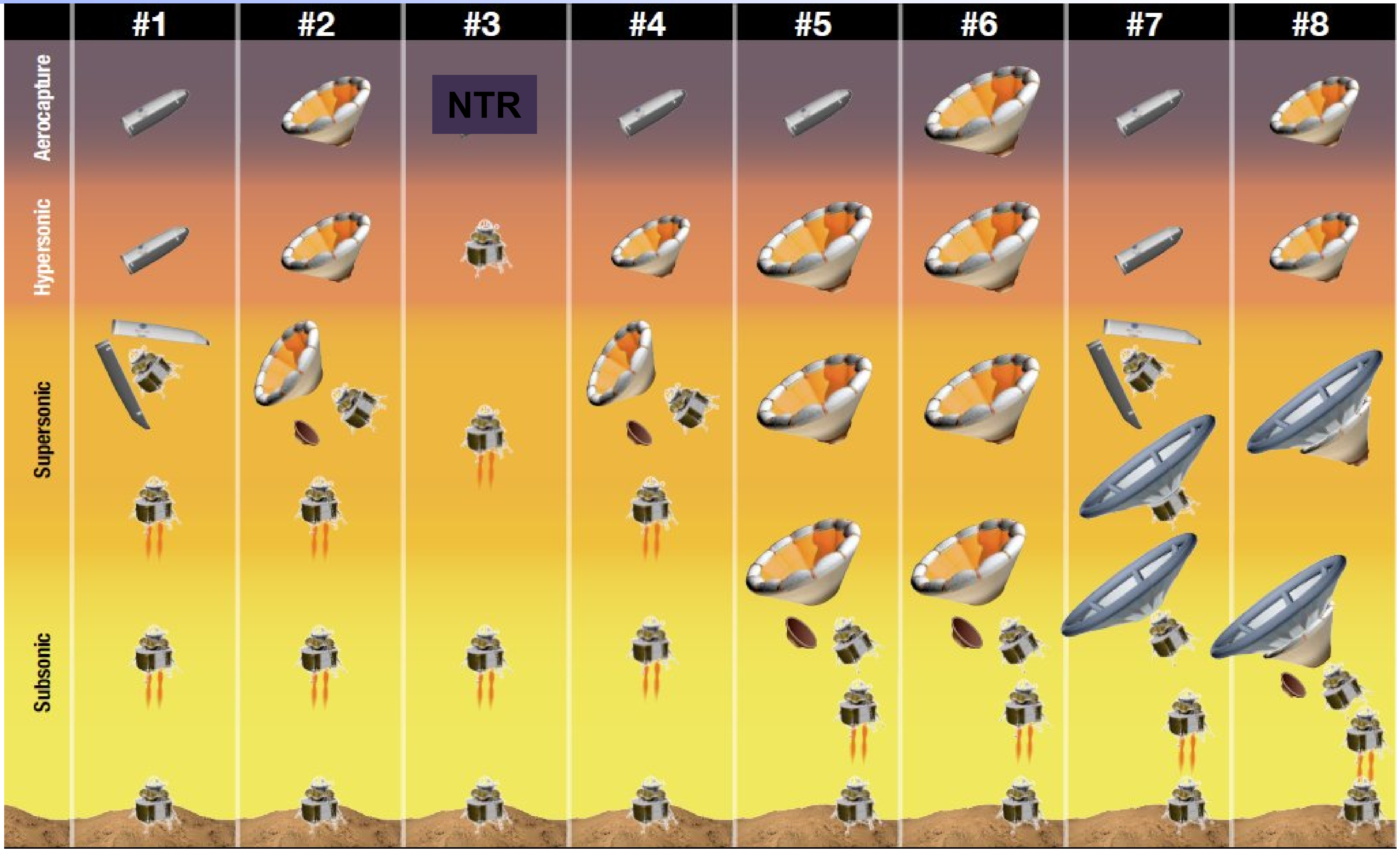



Mid L/D aeroshell system with angle-of-attack control

High Mach Decelerator Systems

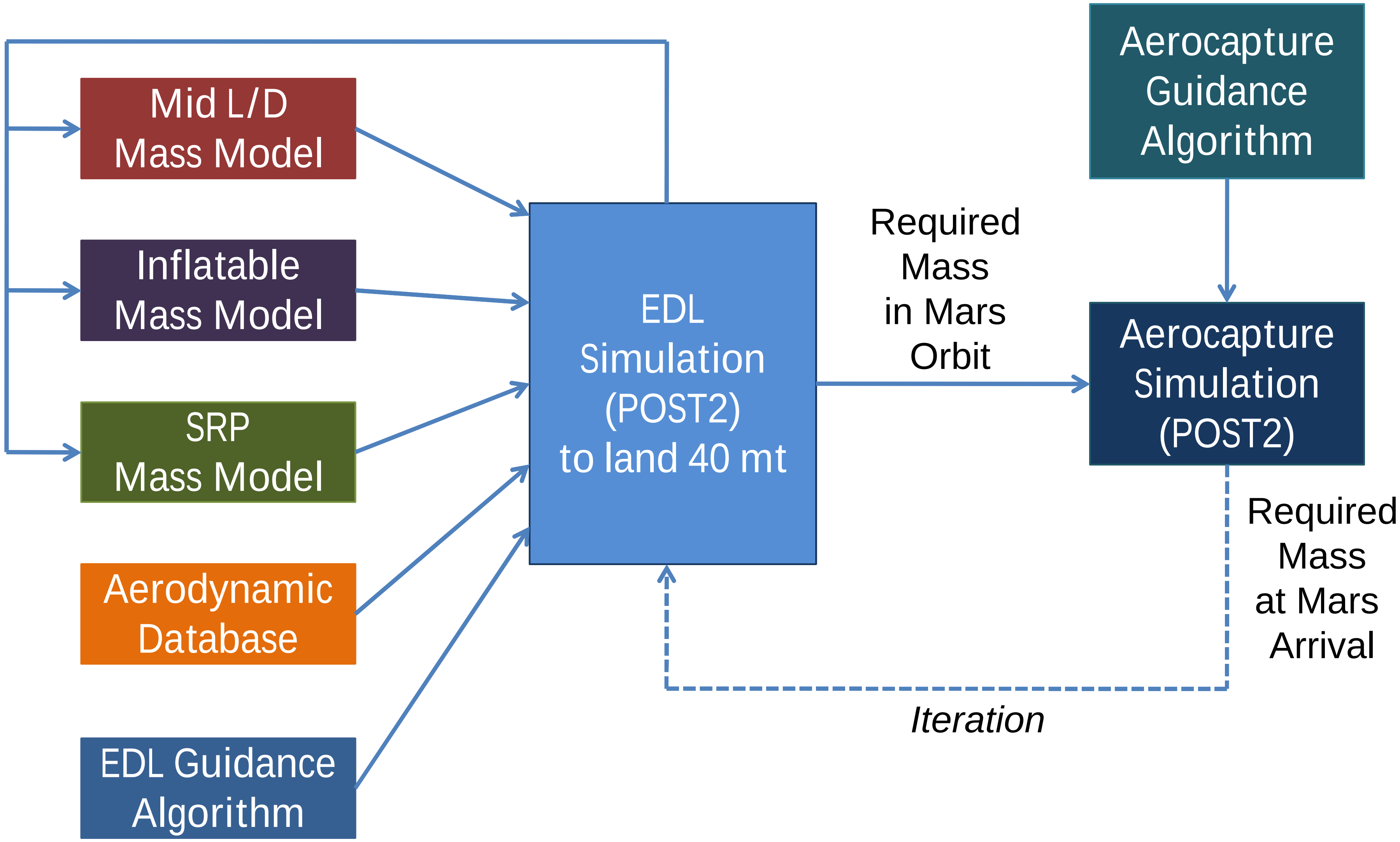
Terminal Descent: Terrain Relative Nav, Hazard Detection and Avoidance

EDL-SA Exploration Architectures – Year 1



Arrival Mass (mt)	110	84	265	109	134	141	107	81

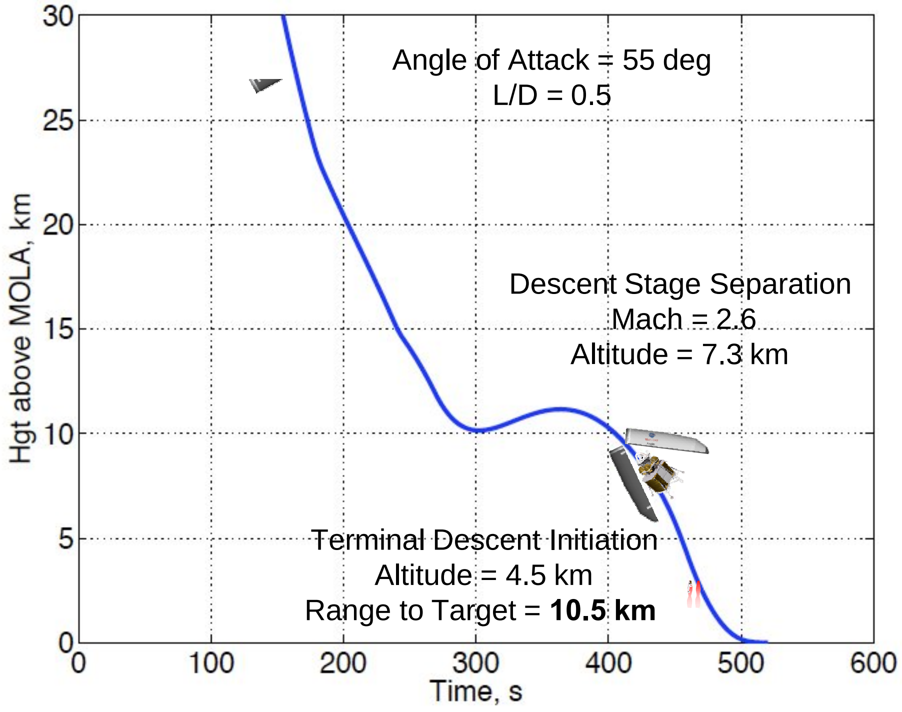
EDL-Systems Analysis Process



Architecture 1 Results

Rigid Aeroshell + Supersonic Retro-propulsion

Reference Trajectory



General Evaluation

- **Selected for similarity to DRA5**
- Increased simulation fidelity from DRA5 for all architectures to identify technologies by including
  - High fidelity mass models (based on RSE's)
  - Theoretical guidance
  - Updated aerodynamics
  - Descent Throttle Profile
  - Precise landing capabilities
- Highest TRL of drag devices considered

Parameter	Arch 1
Arrival Mass [t]	110.1
Ballistic Coefficient [kg/m²]	*396.1*
Deorbit Mass [t]	109.2
Aeroshell Mass TOTAL [t] (minus RCS System)	28.9
Aeroshell Structure Mass [t]	18.3
Aeroshell TPS Mass [t]	10.6
Descent Stage Mass TOTAL [t]	28.4
Descent Stage Dry Mass [t]	12.3
Descent Stage Prop Mass [t]	16.1
Landed Mass [t]	52.3
Payload Mass [t]	40.0

Technical Challenges

- Aeroshell Packaging
- Aeroshell Separation
- Supersonic Retro-propulsion

Pros

Rigid aeroshell is, relative to other concepts, high TRL

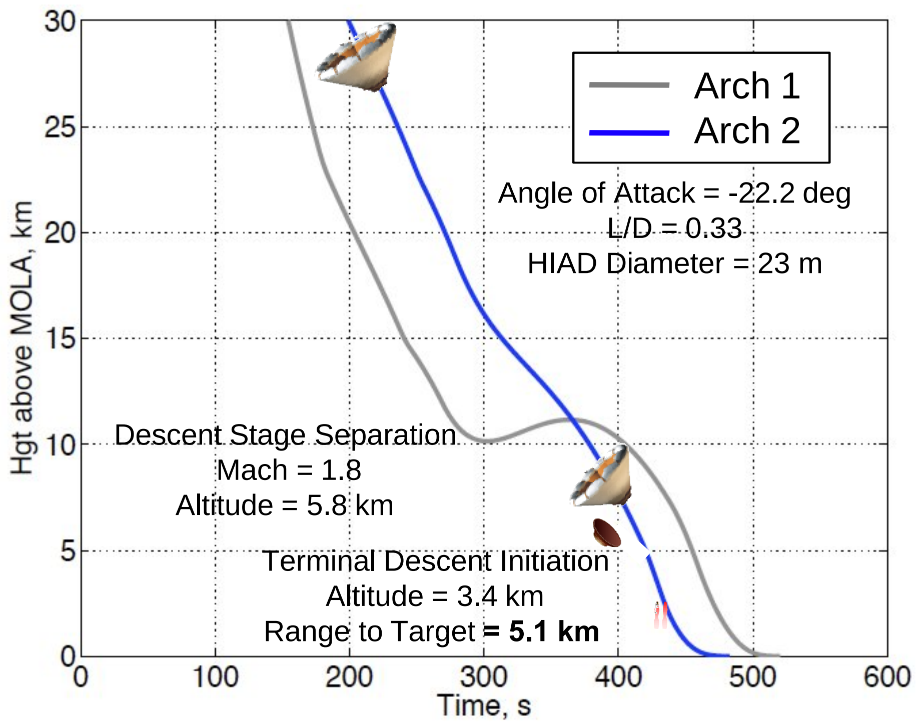
Cons

High Ballistic Coefficient

Architecture 2 Results

HIAD + Supersonic Retro-propulsion

Reference Trajectory



Technical Challenges

- HIAD Packaging
- HIAD Separation
- Supersonic Retro-propulsion
- Dual use HIAD

Pros	Cons
2nd Lightest entry mass	Low TRL compared to other concepts considered

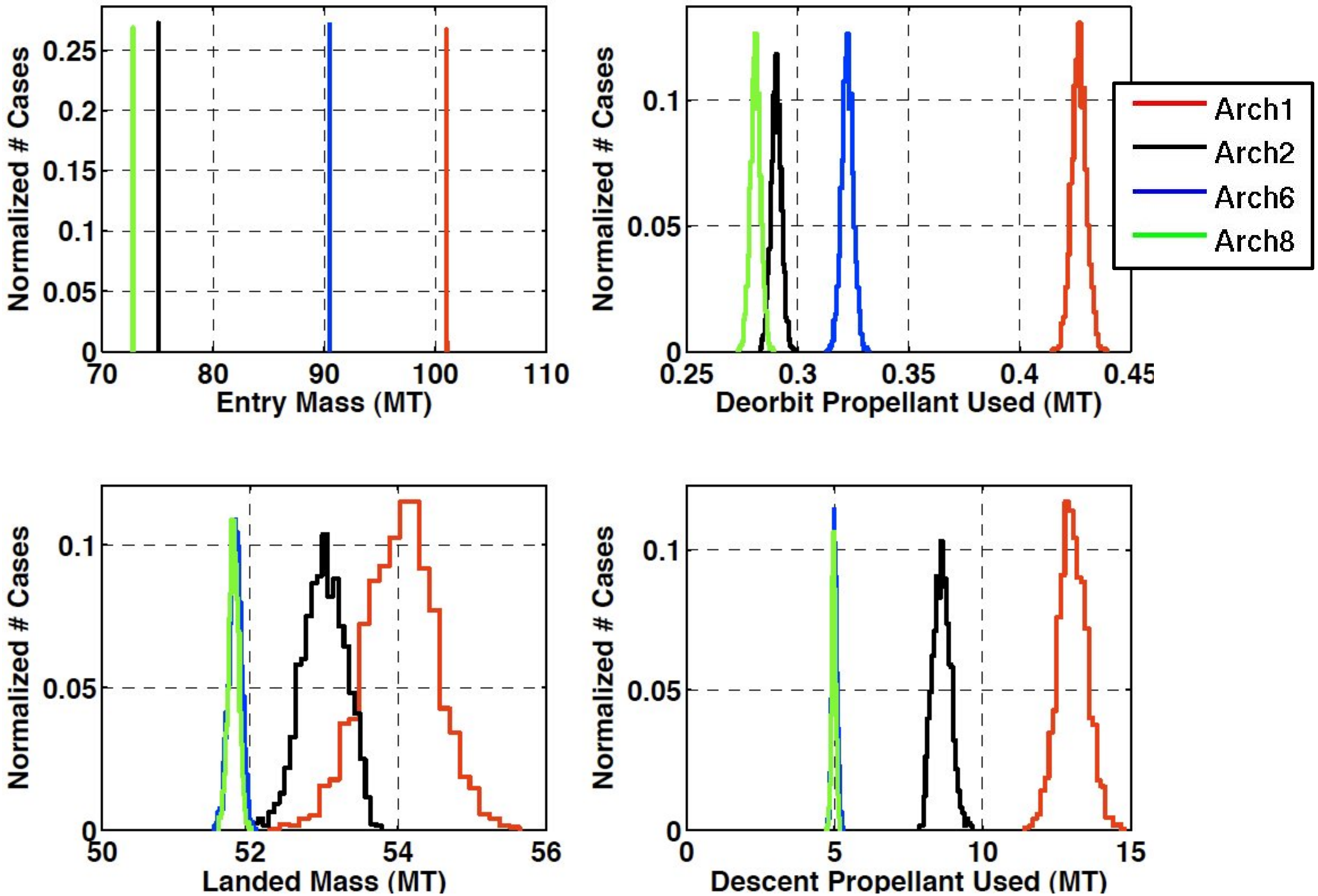
General Evaluation

- **Selected to evaluate mass savings of using a dual use HIAD over a rigid aeroshell**
  - Based on MIAS concept
  - HIAD sized for dual use (aerocapture + entry)

TRADE: Lower TRL concept reduces arrival mass by 26 t over Arch 1

Parameter	Arch 1	Arch 2
Arrival Mass [t]	110.1	83.6
Ballistic Coefficient [kg/m^2]	*396.1*	*154.0*
Deorbit Mass [t]	109.2	82.8
Aeroshell/HIAD Mass TOTAL [t]	28.9	10.7
Aeroshell/HIAD Structure Mass [t]	18.3	6.0
Aeroshell/HIAD TPS Mass [t]	10.6	4.7
Descent Stage Mass TOTAL [t]	28.4	23.8
Descent Stage Dry Mass [t]	12.3	11.8
Descent Stage Prop Mass [t]	16.1	12.0
Landed Mass [t]	52.3	51.8
Payload Mass [t]	40.0	40.0

Monte Carlo Results: Mass



Architecture Conclusions

Based on Simulation Results Only

- Rigid aeroshell-based **Architecture 1** has entry masses comparable to what was shown in DRA 5
- Inflatable-based **Architectures 2 & 8** have lowest entry masses
- **Architectures 4 & 5** EDL sequence are same as 2 & 6 but include an additional aerocapture vehicle needed for development
- **Architecture 6** has no entry mass advantage over Architecture 1 and has additional EDL timeline issues
- **Architecture 7** is complex, compared to other Architectures

Figures of Merit

Expert Opinion

Simulation/Analysis

Past Studies

- **Safety and Mission Success**
  - Probability of Loss of Mission
  - Probability of Loss of Crew
- **Performance and Effectiveness**
  - Sensitivity to Usable Payload Mass to Surface
  - Sensitivity to Surface Elevation
  - Sensitivity to Landing Precision
  - Sensitivity to Environmental Variability
- **Programmatic Risk**
  - Technology Development Risk
  - Programmatic Cost and Schedule Risk
- **Affordability and Life Cycle Cost**
  - Technology Development Cost
  - System Life-Cycle Cost
- **Applicability to Other Missions**
  - Applicability to Mars Robotic Missions
  - Applicability to Other Planetary Missions

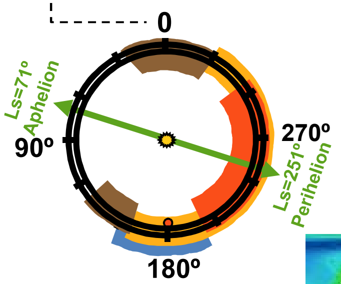
Architecture Sensitivities

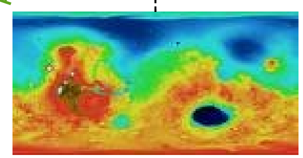
<u>FOMs</u>

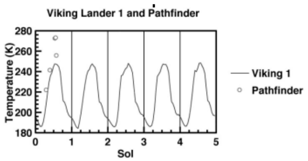
1. Sensitivity to Mission Loss.
2. Sensitivity to Crew Loss.
3. Sensitivity to DeOrbit Mass.
4. Sensitivity to Location.
5. Sensitivity to Environmental Variability.

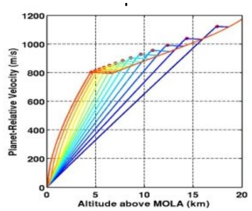
Sensitivity Simulation/Analysis

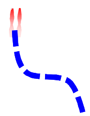
- Sensitivity of arrival mass to atmospheric variability, topography, latitude, etc.
  - **1,2,3,4,5** — Environment (Nominal Flight)
    - L_S
    - Dust Tau
    - Latitude
    - Landing Altitude
    - Time of Day
- Sensitivity of arrival mass to engine capability
  - **1,3** — Performance (Mass Model)
    - T/W
    - Retro-Propulsion Aero
    - I_{SP}
- Sensitivity of arrival mass to entry guidance, powered descent, etc.
  - **1,2,3** — Design (Mass/Flight)
    - Aggressiveness
    - Divert
    - Payload / Diameter
    - L/D

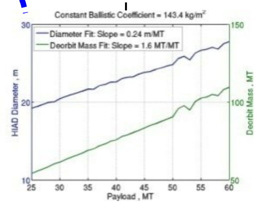


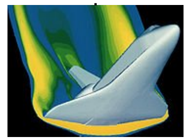








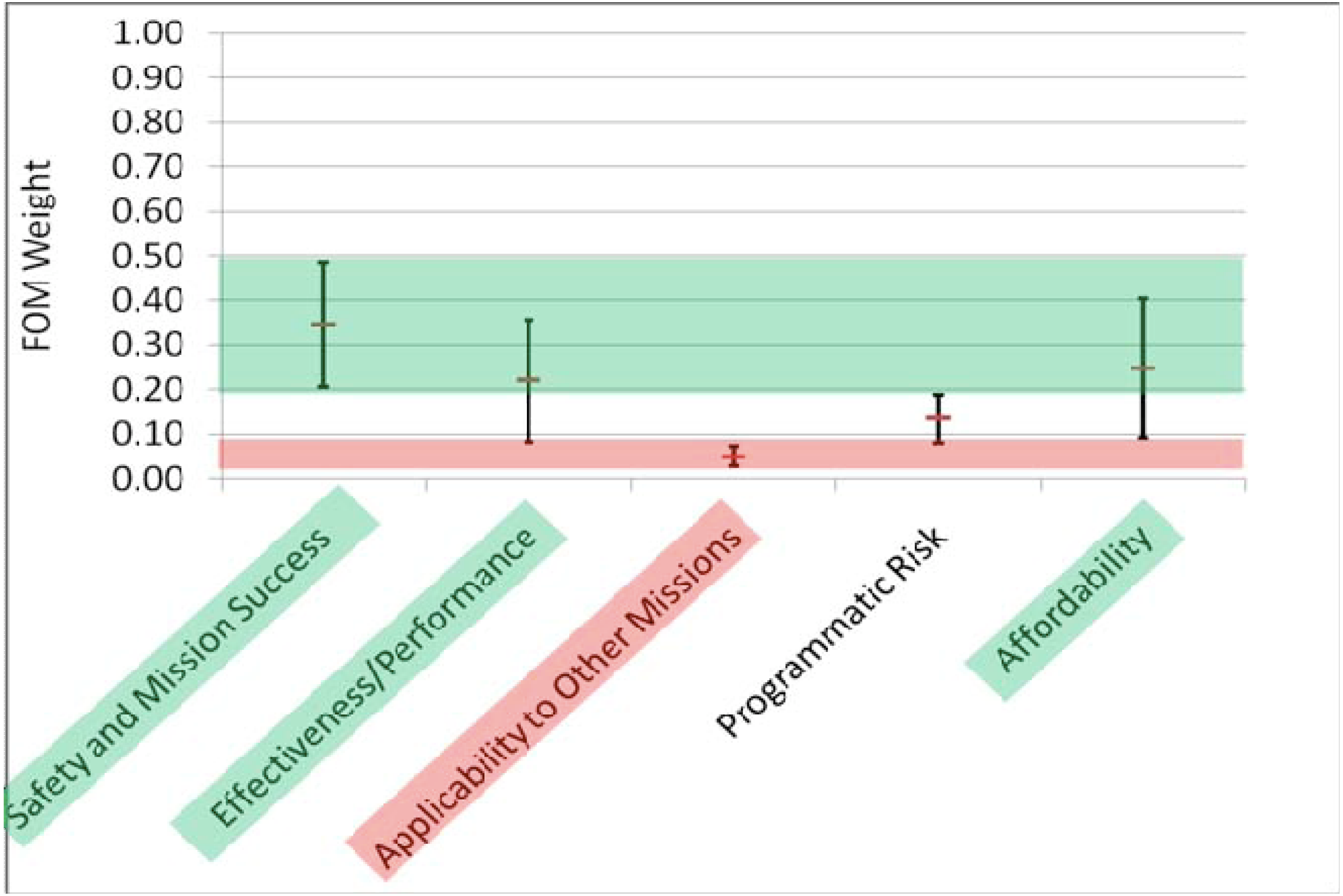




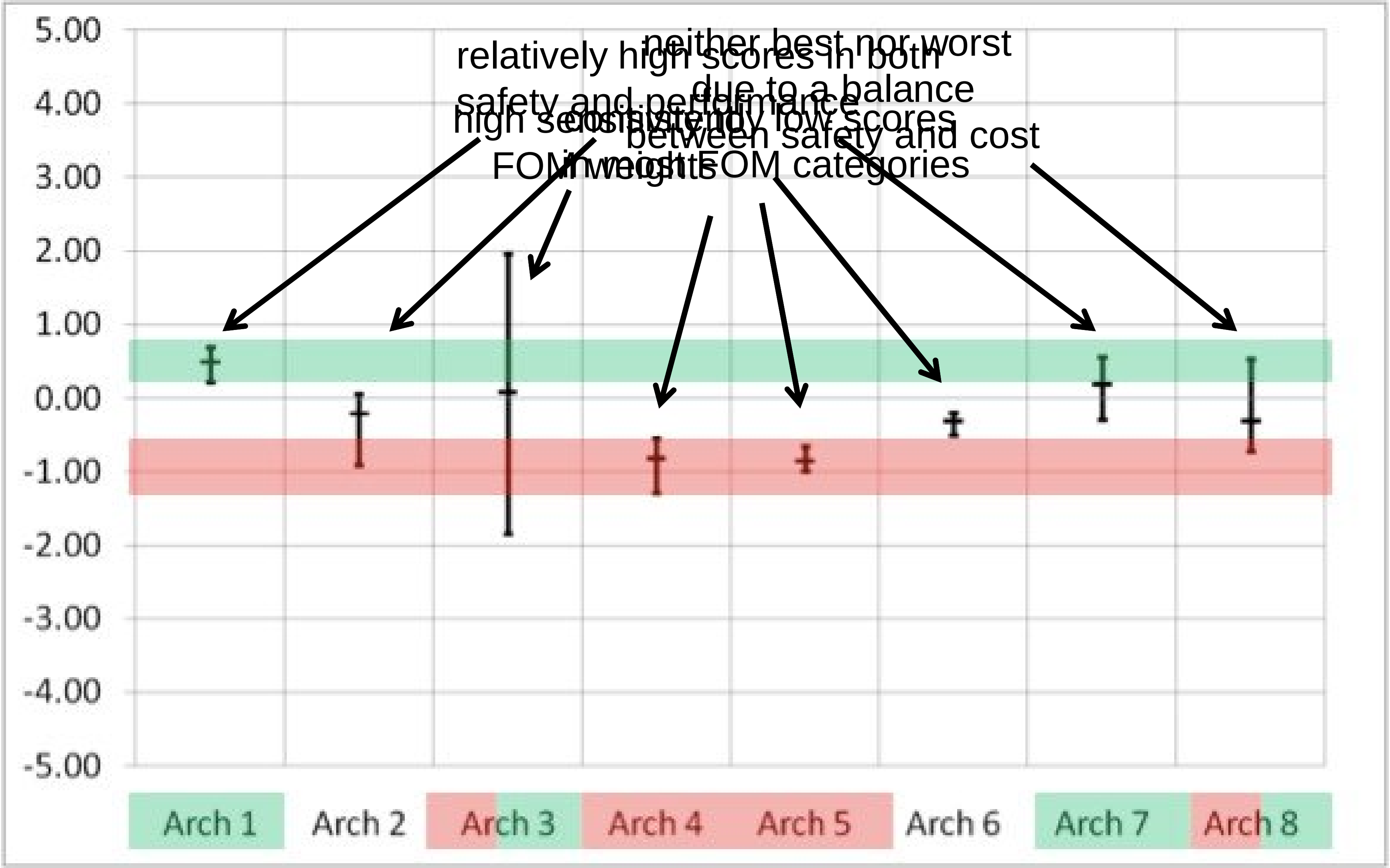
Sensitivity Conclusions

- Due to the entry velocity and mass considered, the exploration class vehicle performance is insensitive to environmental effects. (with the exception of winds on large SIADs at low altitudes)
- Thrust to weight is important for powered descent, not arrival mass
- Due to low engine on-times, I_{sp} has little effect on system mass
- Supersonic retro-propulsion aero augmentation provides minimal benefit to mass
- Mass sensitivity is minimal for improved L/D
- The required propellant for a fixed size divert is proportional to the velocity at engine ignition
- Powered descent aggressiveness is the largest sensitivity to arrival mass
- Changing the diameter of the inflatable decelerator allow trajectories to maintain constant ballistic coefficient for various payload masses

FOM Weights by Program Managers



FOM Scoring Results



Year 1 Technology Recommendations
Exploration-Class

- Key Technology Areas
  - ✓Aeroshell/TPS Design and Development
  - ✓Supersonic Retro-propulsion Development
  - ✓Deployable/Inflatable Decelerator Development
  - ✓Terrain-Relative Navigation/GN&C Development
  - – Aerocapture Development
- Key Sub-Scale System Tests
  - – Supersonic Retro-Propulsion Flight Test Program
  - ✓Deployable/Inflatable Decelerator Flight Test Program
  - – Aerocapture Flight Test

✓ *Denotes inclusion of some funding in a NASA technology program in current/next year*

Year 1 Robotic Study on Parachute Use

OBJECTIVES:

1) Determine a reasonable parachute implementation to land 1.5 mt at 0 km MOLA including an estimate of the propulsion and propellant requirements
2) Determine feasibility of packaging the payload, propulsion and propellant requirements into an MSL-type entry vehicle

DESIRES:

- Avoid the need for a parachute flight qualification test program
- Preserve MSL heritage as much as possible
  - 4.5 m diameter aeroshell, lift/drag, number of engines, prop load, etc…

Relaxation of the above desires is required and supersonic flight testing is necessary

Summary of Supersonic Results

- **Feasible parachute performance is achieved if the timeline margin constraint is satisfied, i.e., timeline margin > 15 s**
- **Chute deploy Mach numbers correspond to 3σ high values**

	Disk-Gap-Band	Ringsail
SINGLE PARACHUTE	1st chute 32.5 m Mach=2.5 n/a	1st chute 31.5 m Mach=2.5 n/a
DUAL PARACHUTE	1st chute 21.5 m Mach=2.5 2nd chute 41.5 m Mach=1.5	1st chute 21.5 m Mach=2.5 2nd chute 41 m Mach=1.5
REEFED PARACHUTE	Reefed 21.5 m Mach=2.5 Disreefed > 34 m Mach=2.0	Reefed 21.5 m Mach=2.5 Disreefed 34 m Mach=2.0

Resultant single and dual chute solutions have lower probability of success due to loads and inflation concerns resulting from Mach & large diam combination

Although large in diameter and Mach, reefing enables the best probability of success

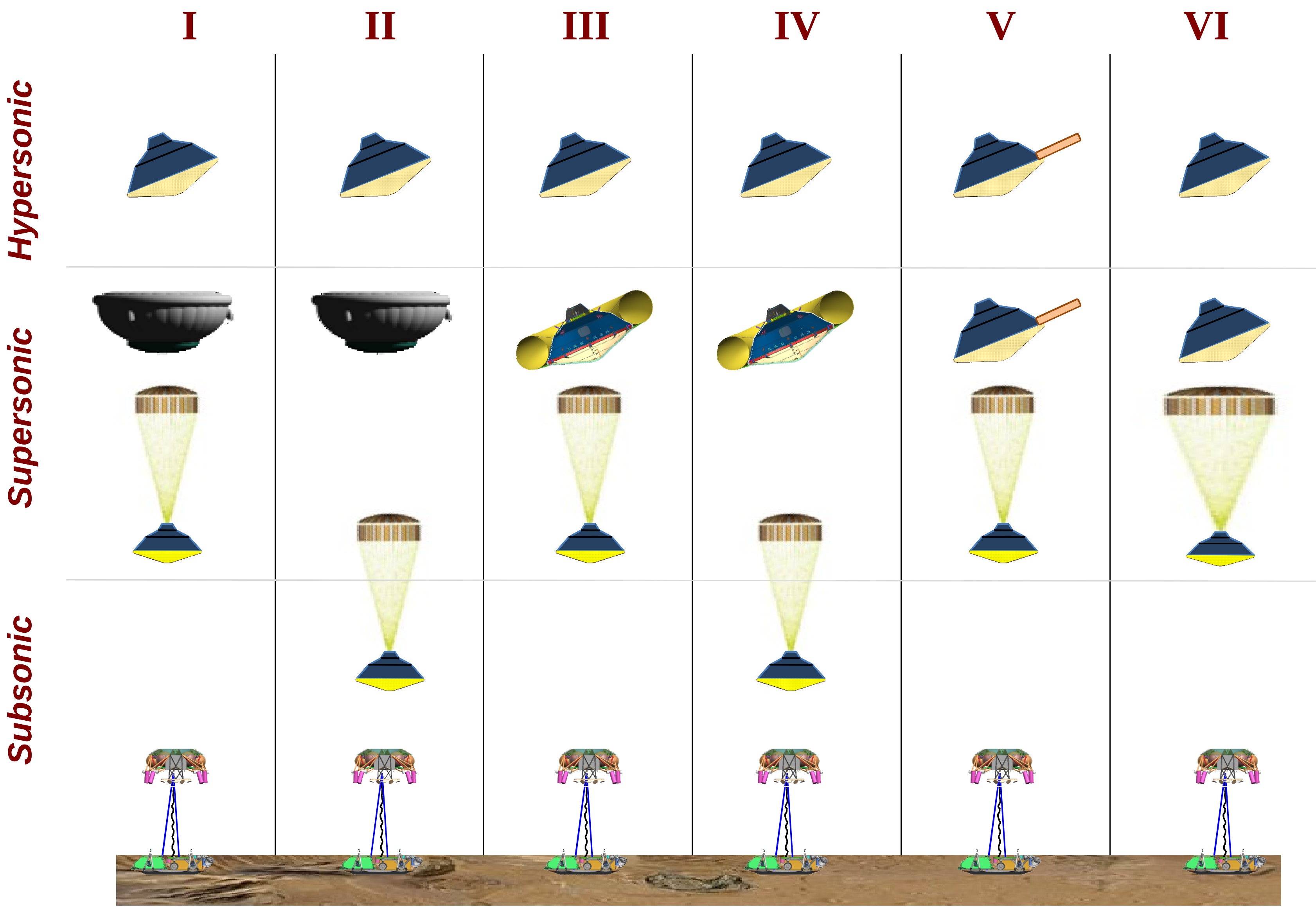
Supersonic Parachute Technology Conclusions/Recommendation

- All parachute solutions capable of landing 1.5 t at 0 km MOLA using an MSL-type vehicle require supersonic flight tests
- Given the certain investment in a flight test, the recommended technology that shows the most promise for success and ultimate capability is a **single 34 m reefed supersonic ringsail**
  - Reefing adds an element of stability which enables larger diameters over an unreefed parachute (i.e., more performance for the money)
  - Single chute option reduces mass compared to the dual chute option
  - Single chute option most likely reduces complexity of deploying two chutes
  - Reefed chute has the potential for implementing varying reefing schemes to tailor drag deceleration as needed
  - The disreefing event is triggered by time, i.e., disreef chute after 9.55 s from chute deploy at Mach 2.5
- The 34 m reefed supersonic ringsail is considered at **TRL5** today
- Supersonic qualification flight test would be required
  - High altitude BLDT (Balloon Launched Decelerator Test)

FY10 Robotic Work

- Year 2 is devoted to large robotic missions. There are two elements for this year:
  - Develop a system using minimum improvements to MSL technology to deliver 1 - 5 MT of landed mass
  - Deliver the same payload, but also provide feed-forward technologies to support the Exploration-class spacecraft development technologies determined in Year 1.

MSL-Improvement Architectures



Feed-Forward Robotic Architecture

- **Launch**
  - Delta IV-H Launch Vehicle
  - 5 m Shroud
  - C3 < 15 km^2/s^2
- **Mars Arrival**
  - $V_{arrival}$ – 7.3 km/s
  - 65 deg sphere cone
  - 7.2 mt @ C3 = 15 km^2/s^2
- **Orbit**
  - MOI via Aerocapture
  - 500 km circular orbit
  - HIAD vehicle class
- **EDL**
  - Entry from orbit – 3.35 km/s
  - HIAD with aeromaneuvering
  - SRP – Mach 2 to 0 (surface)
  - G limit - TBD
- **Payload**
  - 2+ mt
  - Mass Properties – TBD
  - Load Path/Attach pts - TBD
- **Landing Site**
  - 0 km MOLA
  - Precision < 50 m
  - HDA by ALHAT – not modeled
- **Separation**
  - Transitions to be modeled
  - 1 km "Keep out zone"

3

Summary

- The EDL-SA Study was commissioned by the NASA Strategic Management Council to recommend technology development projects based on requirements-driven systems analysis
- The Year 1 (2009) focus was on Exploration-class missions (20–50 mT of landed payload) with some work on parachutes for an MSL+ mission
- The focus in 2010 is large robotic-class missions (1–5 mT of landed payload)
- Preliminary EDL Technology investment areas have been identified based on simulation results
  - Inflatable decelerator and SRP merits clearly shown; alternatives also recommended
  - Study outputs and preliminary roadmapping efforts have influenced and supported technology program investments
- Year 3 roadmapping efforts are subject to change under new NASA technology organization

Backup

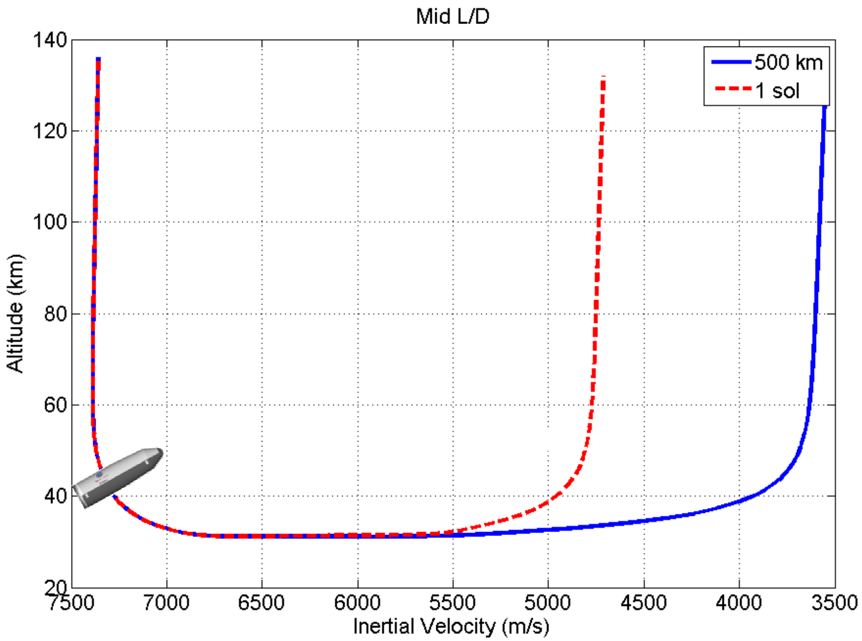
AEDL Technology Models

(Similar Models Same Color)

	Aerocapture	Hypersonic	Supersonic	Subsonic
Arch 1 Rigid Mid L/D to SRP	Rigid Mid L/D	Rigid Mid L/D	Propulsion	Propulsion
Arch 2 HIAD to SRP	Lifting HIAD	Lifting HIAD	Propulsion	Propulsion
Arch 3 All Propulsive	NA (NTP)	Propulsion	Propulsion	Propulsion
Arch 4 Rigid Aerocapture, HIAD to SRP	Rigid Mid L/D	Lifting HIAD	Propulsion	Propulsion
Arch 5 Rigid Aerocapture, HIAD until Subsonic	Rigid Mid L/D	Lifting HIAD	Same, Lifting HIAD	Propulsion
Arch 6 HIAD until Subsonic	Lifting HIAD	Same, Lifting HIAD	Same, Lifting HIAD	Propulsion
Arch 7 Rigid to Drag SIAD	Rigid Mid L/D	Rigid Mid L/D	Drag SIAD	Propulsion
Arch 8 HIAD to Lifting SIAD	Lifting HIAD	Same, Lifting HIAD	Lifting SIAD (extendable skirt)	Propulsion

Aerocapture: Rigid Mid-L/D Aeroshell

Reference Trajectory



Technical Challenges

- Aeroshell Packaging
- Dual Use Aeroshell/TPS

Pros

- Higher TRL than HIAD

Cons

- Higher ballistic coefficient than HIAD

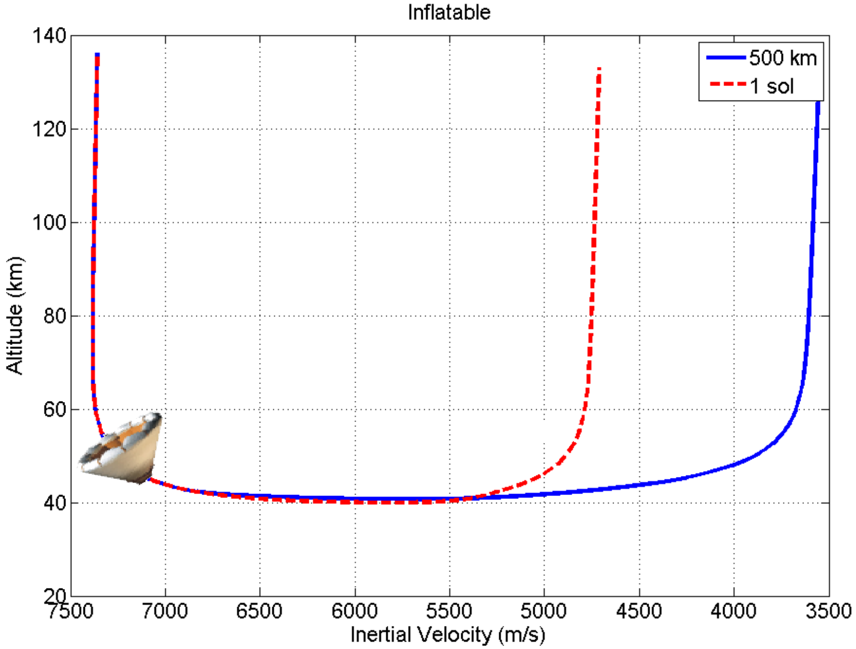
General Evaluation

- 1 sol orbit requires less post-aerocapture orbit adjust propellant

Parameter	500 km	1 sol
Pre-Aerocapture Mass [mT]	152.5	152.5
Ballistic Coefficient [kg/m^2]	*490*	*490*
L/D (at alpha = 55 deg)	*0.43*	*0.43*
Propellant Mass Available [mt]	6.2	6.2
Nominal DV Used [m/s]	*111.2*	*14.4*
Isp [sec]	369	369
Propellant Used (nominal) [mT]	4.6	0.6
Captured Mass [mT]	147.9	151.9

Aerocapture: Inflatable (HIAD)

Reference Trajectory



Technical Challenges

- HIAD Packaging
- Dual use HIAD

Pros

- Lower ballistic coefficient than rigid aeroshell

Cons

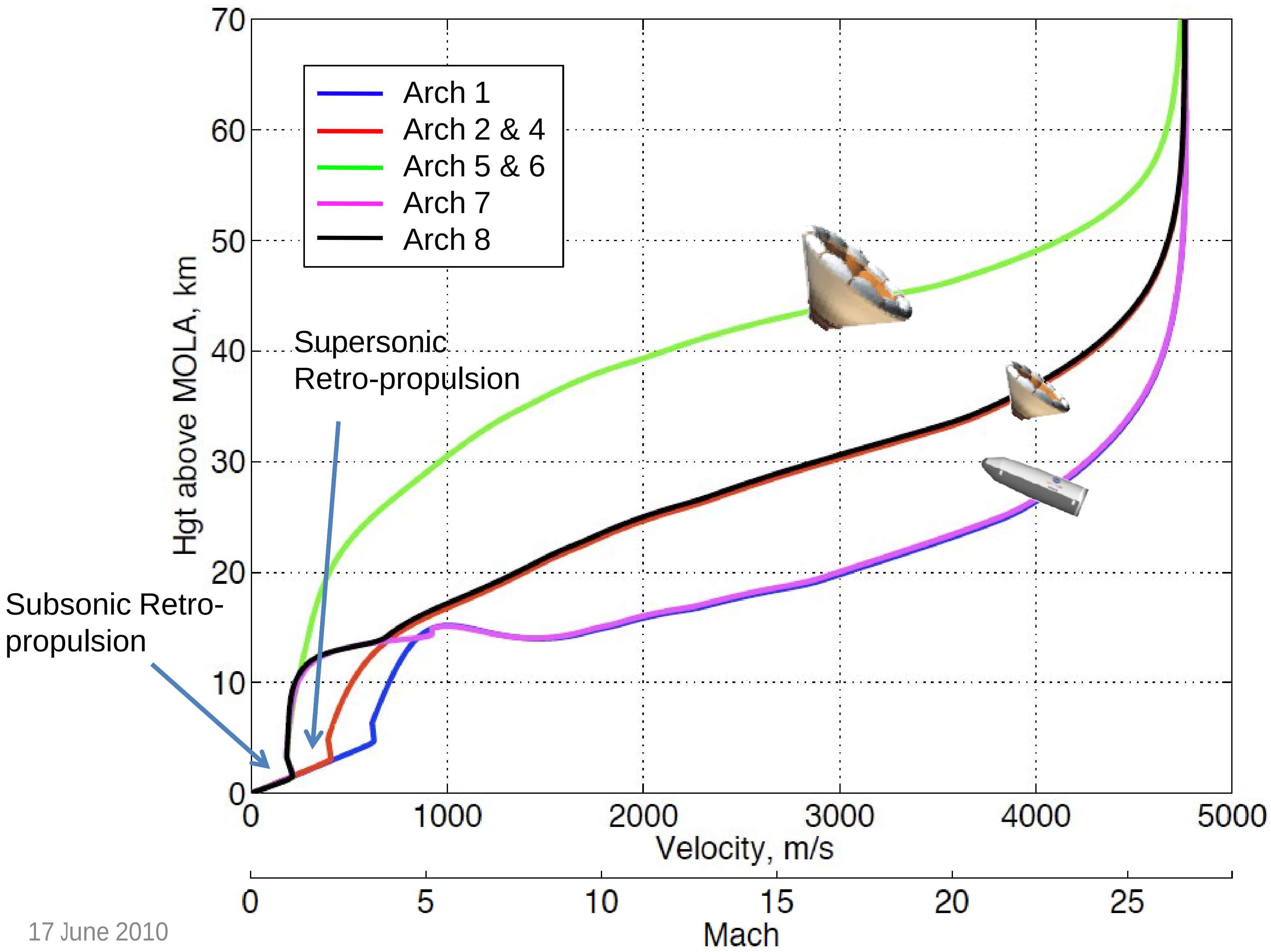
- Lower TRL than rigid aeroshell
- More difficult to control than rigid

General Evaluation

- 1 sol orbit requires less post-aerocapture orbit adjust propellant

Parameter	500 km	1 sol
Pre-Aerocapture Mass [mT]	93.0	93.0
Ballistic Coefficient [kg/m^2]	*165*	*165*
L/D (at alpha = 20 deg)	*0.3*	*0.3*
Propellant Mass Available [mt]	3.8	3.8
Nominal DV Used [m/s]	*108.0*	*15.5*
Isp [sec]	*369*	*369*
Propellant Used (nominal) [mT]	2.7	0.4
Captured Mass [mT]	90.3	92.6

Exploration-Class Reference Trajectories



DRA5 vs. EDL-SA Configuration Comparison

DRA 5	EDL-SA
Entered from 1 sol orbit only	Considered entry from a 500 km and a 1 sol orbit
Used in plane psuedo guidance (no reversals)	Used a theoretical guidance that nominally included 3 bank reversals
No separation event	Included a 10 second separation event to jettison the inflatable or aeroshell prior to terminal descent engine initiation
Entry designed to hold 2 g's on entry	Constrained to a maximum of 4 g's on entry
Maintained constant 3 g's on descent engines	Maintains nominal maximum 2.5 g's on descent engines peaking just after engine initiation and linearly decreasing until landing for increased controllability
No Monte Carlo Analysis was preformed	Monte Carlo and Sensitivity analysis
Simple mass model with varying component margins	Detailed mass models based on response surface equations
10x30 m aeroshell	
40 mt Payload	
Require vehicle to hold 2.5 m/s for 5 seconds prior to touch down	
Thrust to weight of the descent system = 3 g's; Thrust to weight of engines is 80 lbf/lbm	
Targeted 0 km above MOLA areoid	
Targeted equatorial landing (Fixed only for EDL-SA)	

Design Sensitivity

Sensitivity	Nominal Value	Sensitivity Range	Arrival Mass Change				
			Arch 1	Arch2	Arch6	Arch7	Arch8
Divert Maneuver	0 km	0:0.5:3.0	-0.1 MT (-0.1 %) / 0.5 km	-0.3 MT (-0.4 %) / 0.5 km	-4.1 MT (-4.4 %) / 0.5 km	N/A	-2.5 MT (-3.4 %) / 0.5 km
Extra Propellant	0 MT	0:0.5:5.0	1.9 MT (1.84%) / MT Prop	1.93 MT (2.51 %) / MT Prop	2.72 MT (2.95%) / MT Prop	1.74 MT (1.8 %) / MT Prop	1.74 MT (2.4 %)/ MT Prop
Payload	40 MT	10:5:60	1.72 MT (1.67 %) / MT Payload	1.79 MT (2.33 %) / MT Payload	2.29 MT (2.48 %) / MT Payload	1.54 MT (1.59 %) / MT Payload	1.71 MT (2.34 %) / MT Payload
L/D	0.51 Rigid 0.33 Inflat	75%:125%	-0.104 MT (-0.1 %) / 10% Ca	-0.168 MT (-0.22 %) / 10% Ca	N/A	N/A	N/A

Exploration class vehicle mass growth is most sensitive to design decisions

Environmental Sensitivity

Sensitivity	Nominal Value	Sensitivity Range	Total Mass Variation				
			Arch 1	Arch2	Arch6	Arch7	Arch8
Season (Ls)	~174.5	0:30:360 deg	688 kg (0.7%)	863kg (1.1%)	660kg (0.7%)	334kg (0.4%)	367kg (0.5%)
Dust opacity MarsGRAM dusttau	0.7	0.1:0.2:0.9					
Landing Altitude Above MOLA	0 km	-4:0.2: 2.5 km	3724 kg (3.6%)	2582 kg (3.4%)	1860 kg (2%)	1075 kg (1.1%)	464 kg (0.6%)
Latitude	-1.177	-75:15:75 deg	1555 kg (1.5%)	2053 kg (2.7%)	2146 kg (2.3%)	941 kg (1%)	890 kg (1.2%)
Time of Day	5:30 am	0:1.5:24 hours	591 kg (0.6%)	574 kg (0.8%)	494 kg (0.5%)	430 kg (0.4%)	226 kg (0.3%)

Exploration class vehicle performance is insensitive to environmental effects.

Performance Sensitivity

Sensitivity	Nominal Value	Sensitivity Range	Arrival Mass Change				
			Arch 1	Arch2	Arch6	Arch7	Arch8
Engine Thrust to Weight	80 lb_f/lb_m	50:5:90	-1.1 MT (-1 %) / 10 (lb_f/lb_m)	-1 MT (-1.4 %) / 10 (lb_f/lb_m)	-1.3 MT (-1.4%) / 10 (lb_f/lb_m)	-0.9 MT (-0.93 %) / 10 (lb_f/lb_m)	-0.91 MT (-1.2 %) / 10 (lb_f/lb_m)
Vehicle Thrust to Weight	3 g's	2:0.25:4	0.73 MT (0.71%) / g	0.86 MT (1.1 %) / g	-0.91 MT (-0.98 %)/g	0.63 MT (0.65 %)/g	1.1 MT (1.5 %)/g
Specific Impulse	369 sec	355:2.5:375	-0.61 MT (-0.59 %) / 10 sec	-0.43 MT (-0. 56%) / 10 sec	-0.31 MT (-0. 33 %) / 10 sec	-0.24 MT (-0. 24 %) / 10 sec	-0.25 MT (-0. 34 %) / 10 sec
Supersonic Aero Augmentation	Ca=0	Ca=0:2	-0.104 MT (-0.1 %) / 10% Ca	-0.168 MT (-0.22 %) / 10% Ca	N/A	N/A	N/A

Exploration class vehicle mass growth is insensitive to T/W, Isp, and Thruster Drag Augmentation