A High-Heritage Blunt-Body Entry, Descent, and Landing Concept for Human Mars Exploration

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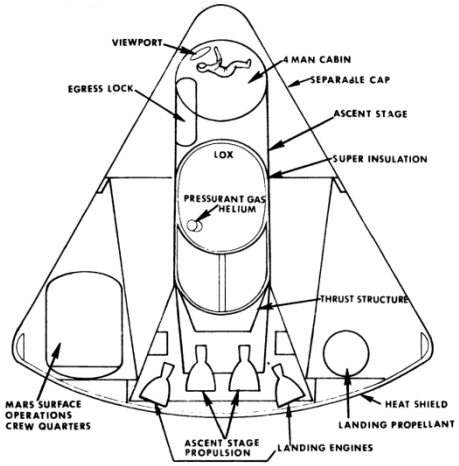
The Crewed Mars Lander Challenge

- Mars lander concepts to support notional crewed missions, including a Mars Ascent Vehicle (MAV), are typically architected to deliver a Useful Landed Mass (ULM) in the range of 15 – 40 t
- Robotic Mars landers to date have all delivered a ULM of < 1 t and used parachutes and sub-sonic retro-propulsion
- Entry, Descent, and Landing (EDL) approaches used to date, for vehicles with ballistic coefficients (β) < 150 kg/m^2, cannot deliver the ULM needed for crewed missions
  - Crewed lander concepts typically have β > 300 kg/m^2
  - Current parachute technology cannot function at the dynamic pressures and velocities required for crewed landers
    - High β entry systems achieve the low Mach (<2.2) conditions needed for parachute deployment too close to the ground, or not at all
  - Crewed landers will need to use Supersonic Retro-Propulsion (SRP)

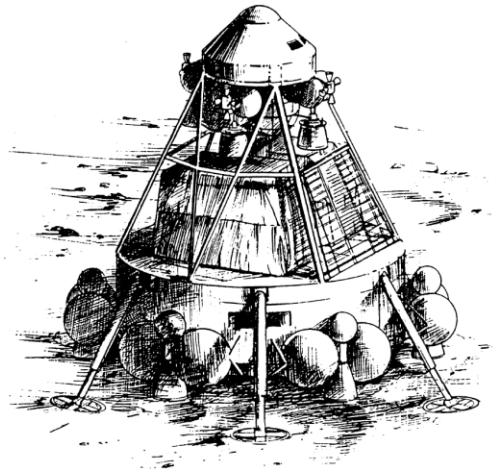
EDL Paradigm Shift

- All previous Mars missions have required that the entry vehicle maintain a low β (50 – 150 kg/m^2). This was needed so that the entry altitude at the transition to parachute deployment near Mach 2 was high enough (8-15 km) to allow adequate time for the remaining EDL steps (heatshield separation, other deployments, and propulsive terminal descent) to complete before hitting the ground.
- With SRP, the requirement to be at high altitude at Mach 2 is eliminated. High thrust-to-weight (T/W) SRP initiation at higher Mach numbers (2-5) and low altitudes is not only feasible, but desirable. This allows the entry vehicle to have much higher mass (per unit heat shield area) and be able to fly at higher dynamic pressures and much lower altitudes (<5 km) during the hypersonic phase.
- The combination of high β entry vehicle and high T/W SRP will be shown to be a powerful combination that can be enabling for large human-scale payloads on Mars.

Selected Previous Studies of High Ballistic Number Blunt Body Mars Lander Concepts



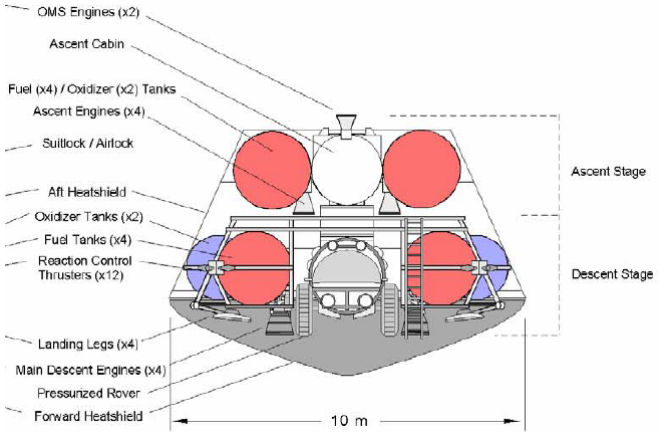
Gordon Woodcock, MSFC, 1966



Scott Geels, MIT, 1990

b) 15 m diameter vehicle

John Christian, Georgia Tech, 2006



SpaceWorks, 2007

Pre-decisional. For discussion purposes only.

Lander Concept – Assumptions and Features

- 10 m diameter blunt-body entry vehicle that would launch in a slight hammer-head configuration on the SLS Block 2
- Ogive-shaped backshell with dual use as the launch fairing on SLS
- 75 t entry mass, based on estimated performance for a two-SLS launch scenario
- Lander would use aerocapture to enter High Mars Orbit (HMO) where it would loiter for an extended time awaiting the arrival of the crew in a separate vehicle
- Non-cryogenic biprop system for descent stage with 6 pump-fed engines
- Notional Mars Ascent Vehicle (MAV) propulsion would use single-stage non-cryogenic high-heritage biprop system with a single pump-fed engine
- Fully-fueled MAV that would allow for abort-to-orbit capability both during EDL and after landing, without requiring any Mars surface infrastructure
- MAV to support crew of 2 for 24 days, 3 for 16 days, or 4 for 12 days
- Ascent is to Low Mars Orbit (LMO) where the MAV would dock with a boost stage in LMO to provide return to HMO
- Aerodynamic MAV moldline with a hinged nosecone to protect the docking system from dust and debris

10 m Crewed Mars Lander Concept

MAV nose cone hinges out for docking access

3.2 m

Ogive backshell/fairing

Crew cabin

Toroidal propellant tanks

Conical shell with cutouts for tanks and engines

8 m

3.0 m

26 t MAV wet mass

Descent stage propellant tanks x 6

MAV sep'n. I/F

Launch vehicle adapter separation point

250 kN engine x 6

250 kN engine (scaled-up RS-72)

2 of 6 engines are gimbaled from 10° to 60° from vertical

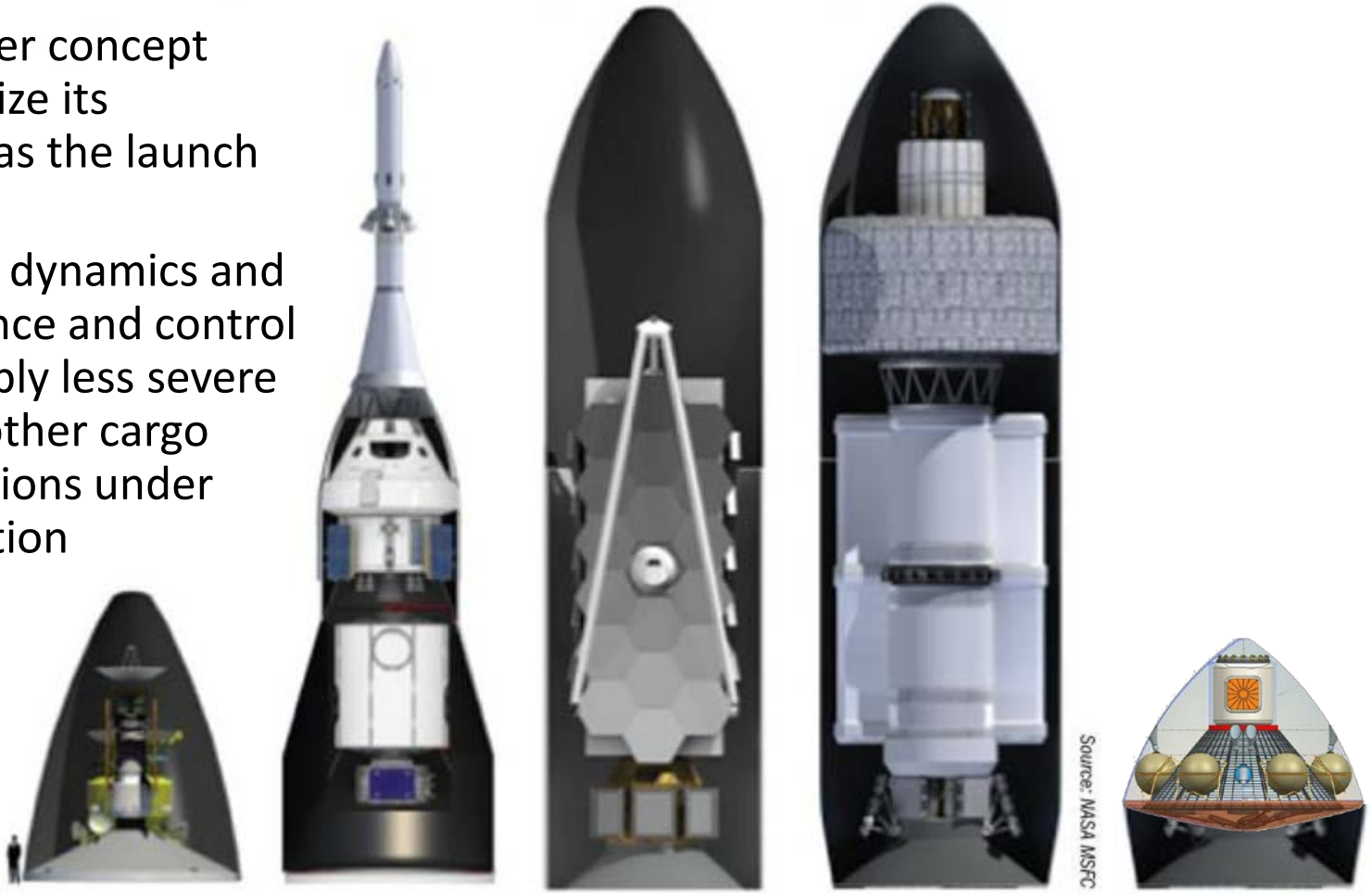
10 m

MAV in flight

H. Price,
11/13/2015

10 m Lander Hammer-Head Launch Configuration Concept

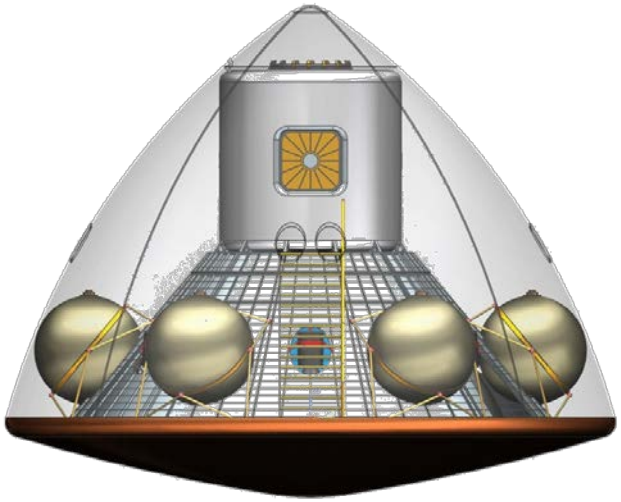
- 10 m lander concept would utilize its backshell as the launch fairing
- Loads and dynamics and L/V guidance and control are probably less severe than the other cargo configurations under consideration



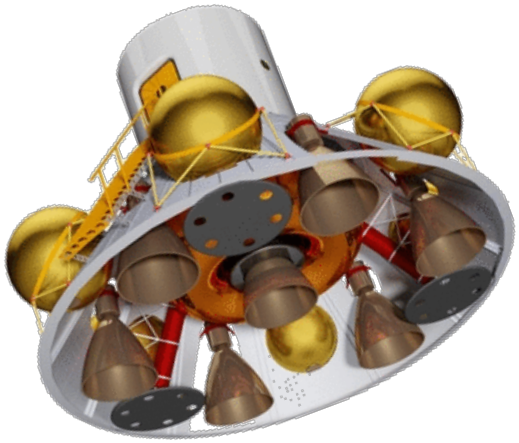
Source: NASA MSFC

Europa Clipper | Universal Stage Adapter with Orion and Small Habitat | 8 meter Fairing with Telescope | 10 meter Fairing with Notional Mars Payload | Notional 10 meter diameter Mars Lander

10 m Descent/Ascent Vehicle Configuration Concept



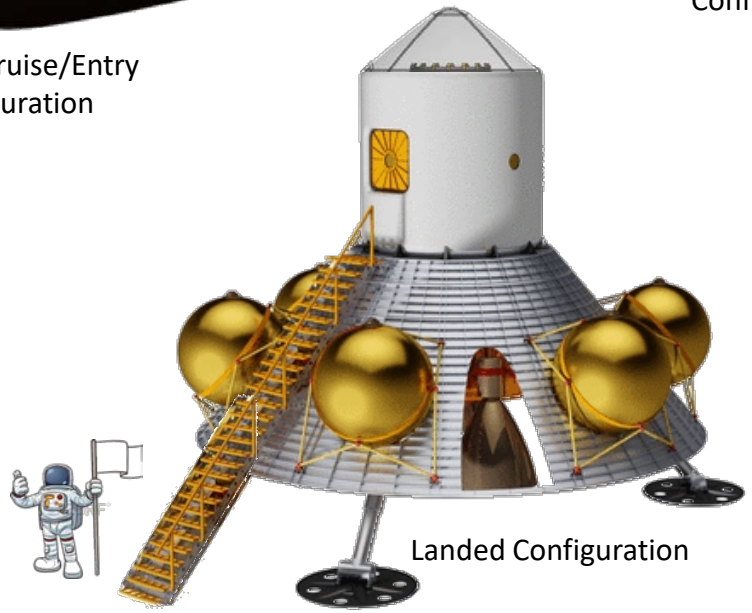
Launch/Cruise/Entry Configuration



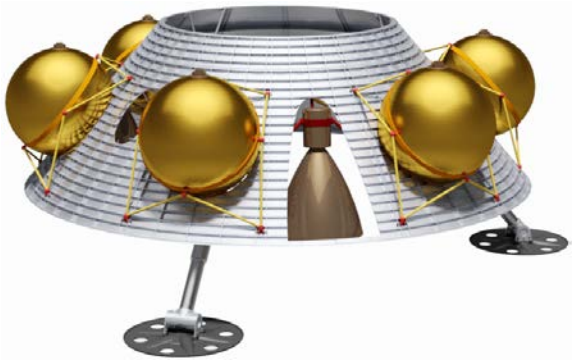
Subsonic Descent Configuration

Toroidal tanks similar to Briz-M

MAV Ascent Configuration

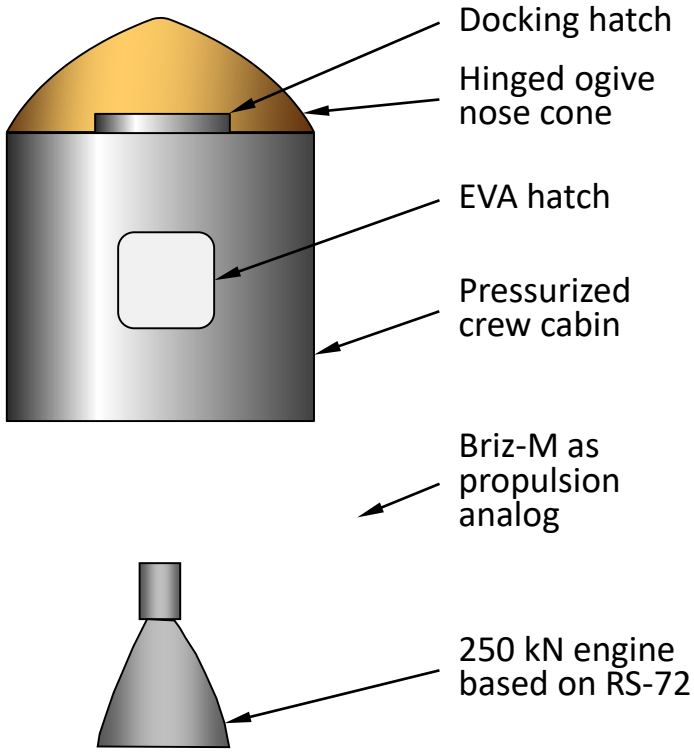


Landed Configuration



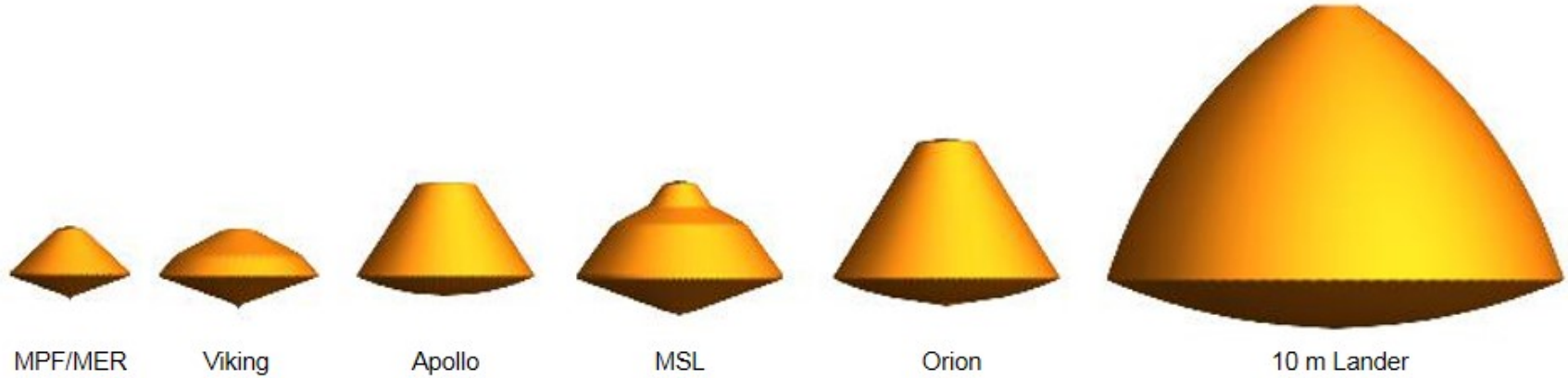
Features of Example MAV Design

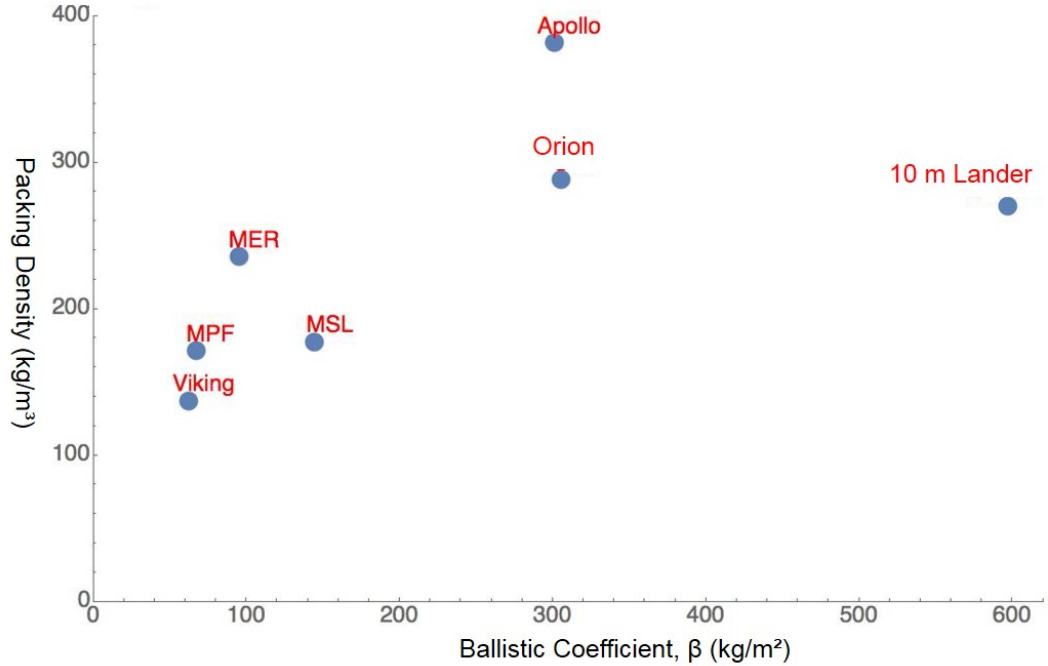
- Simple single-stage non-cryo high-heritage biprop system (MMH/MON-25)
  - Briz-M stage was used as an analog for mass and propellant capacity
  - Single pump-fed engine (example is sized at 250 kN)
- Fully fueled to allow for abort capability during EDL and, after landing, provide for return to orbit without requiring interaction with any Mars surface infrastructure
- Ascent is to Low Mars Orbit (LMO)
  - Must dock with boost stage in LMO to return to High Mars Orbit (HMO)
- Moldline is aerodynamic
  - Hinged nosecone protects docking system from dust and debris
- Concept is to be able to support a crew of 2 for 28 days, a crew of 3 for 14 days, or a crew of 4 for 7 days
  - Seating is reclined and on one level
- No airlock – Apollo LEM style



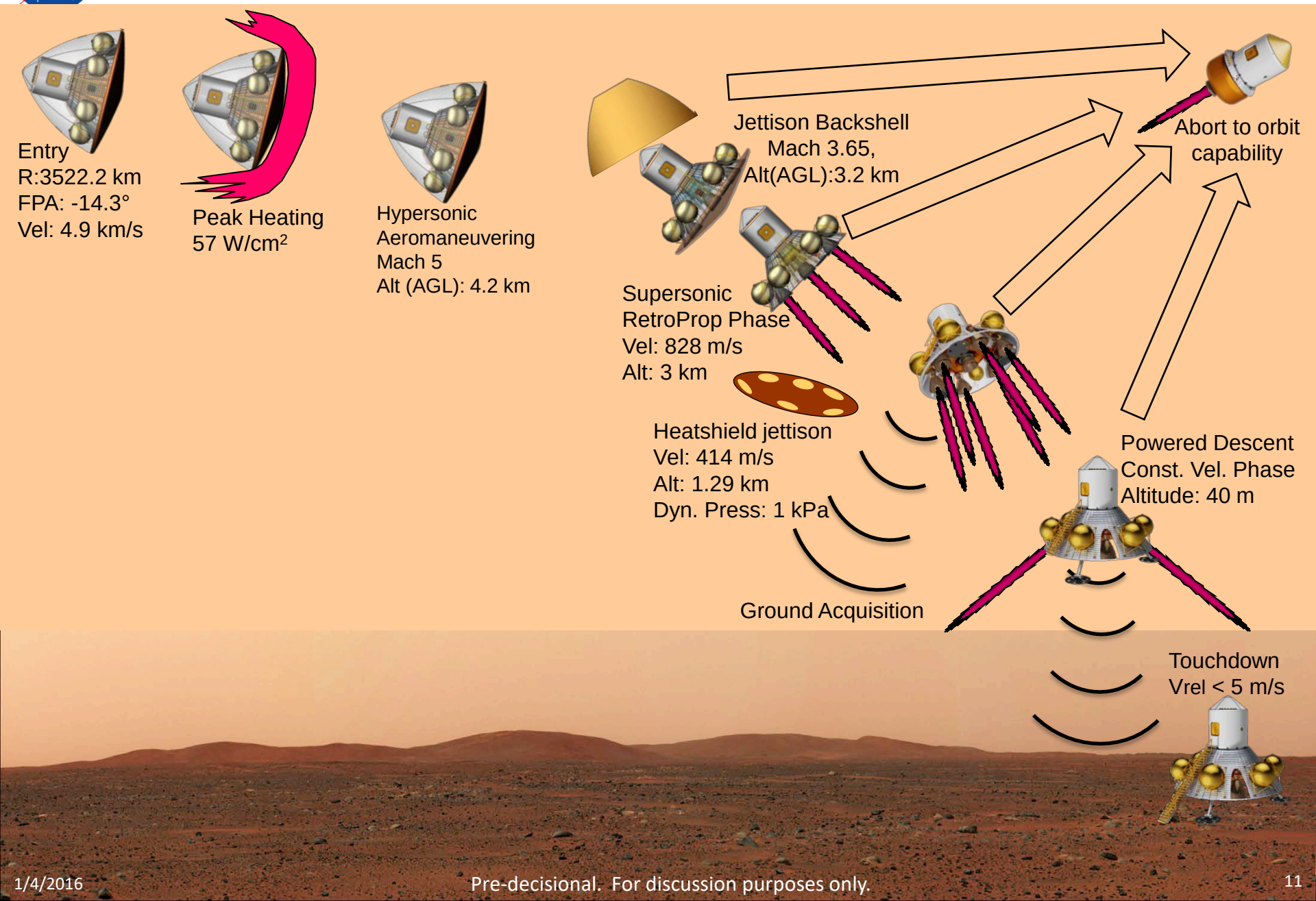
10 m Concept: Size Comparison to Previous Vehicles

Humans to Mars

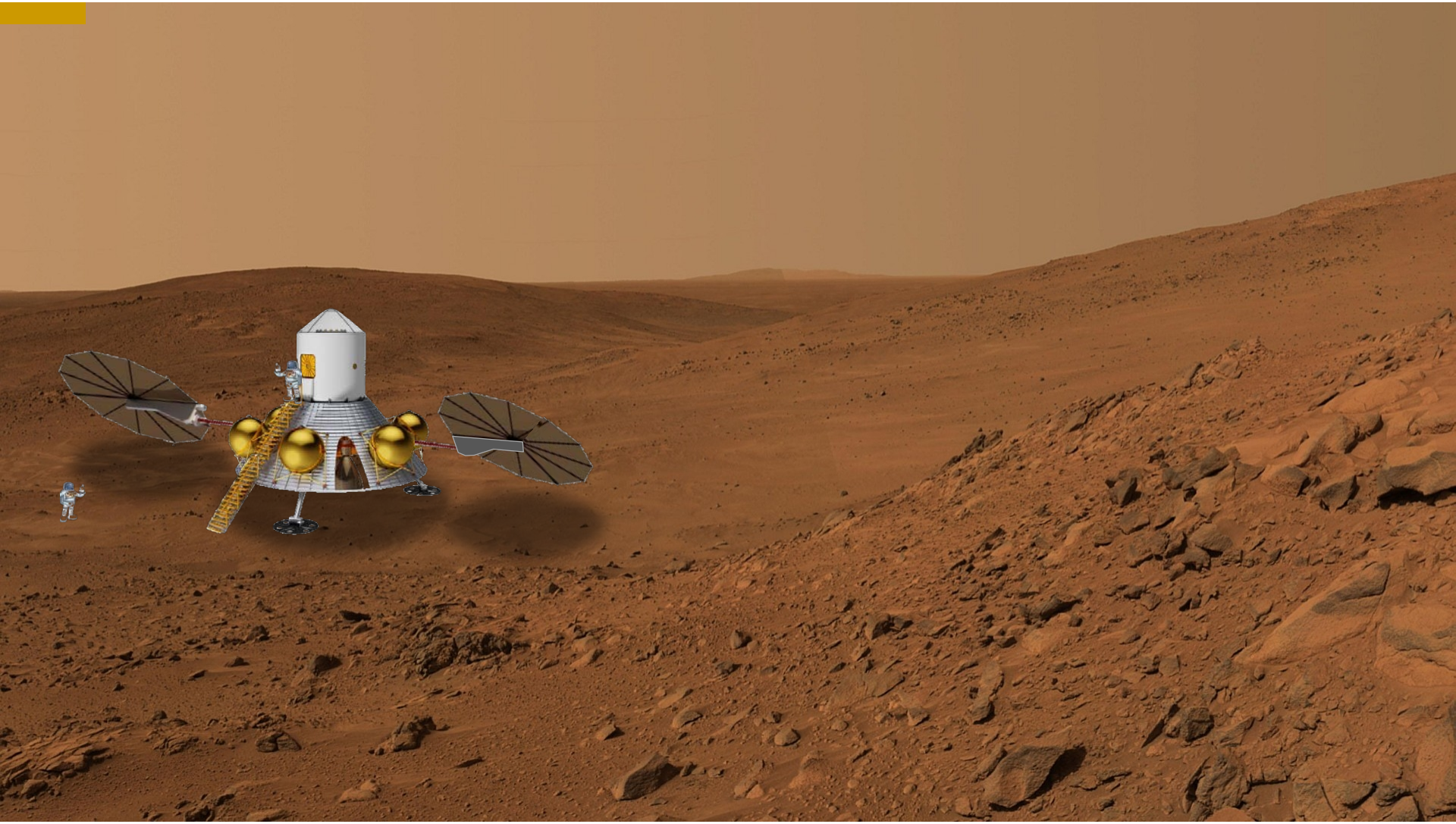




EDL Concept for 10 m Blunt Body Lander



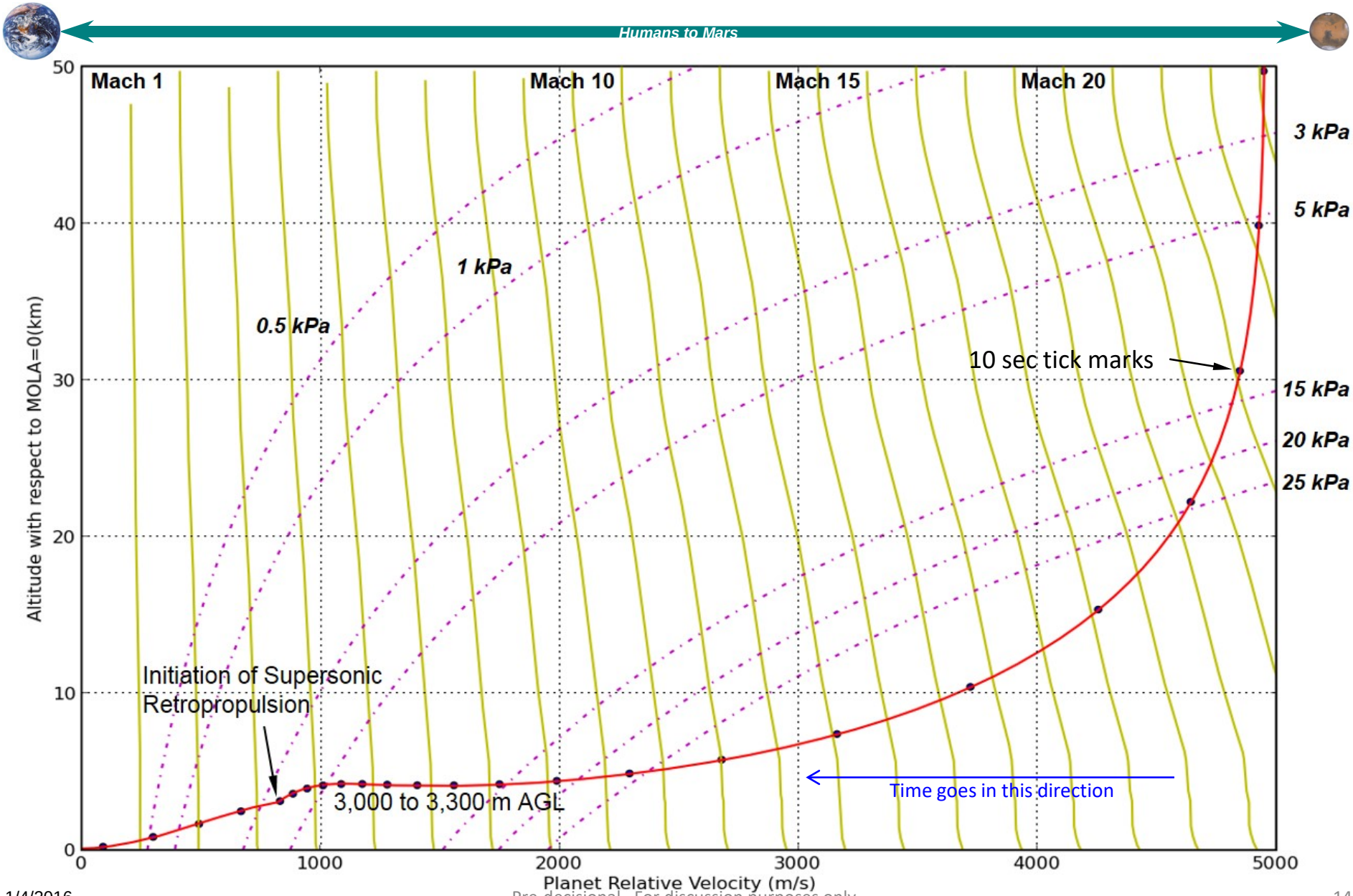
Crewed Mars Descent/Ascent Vehicle Concept



EDL Simulation Approach for Study

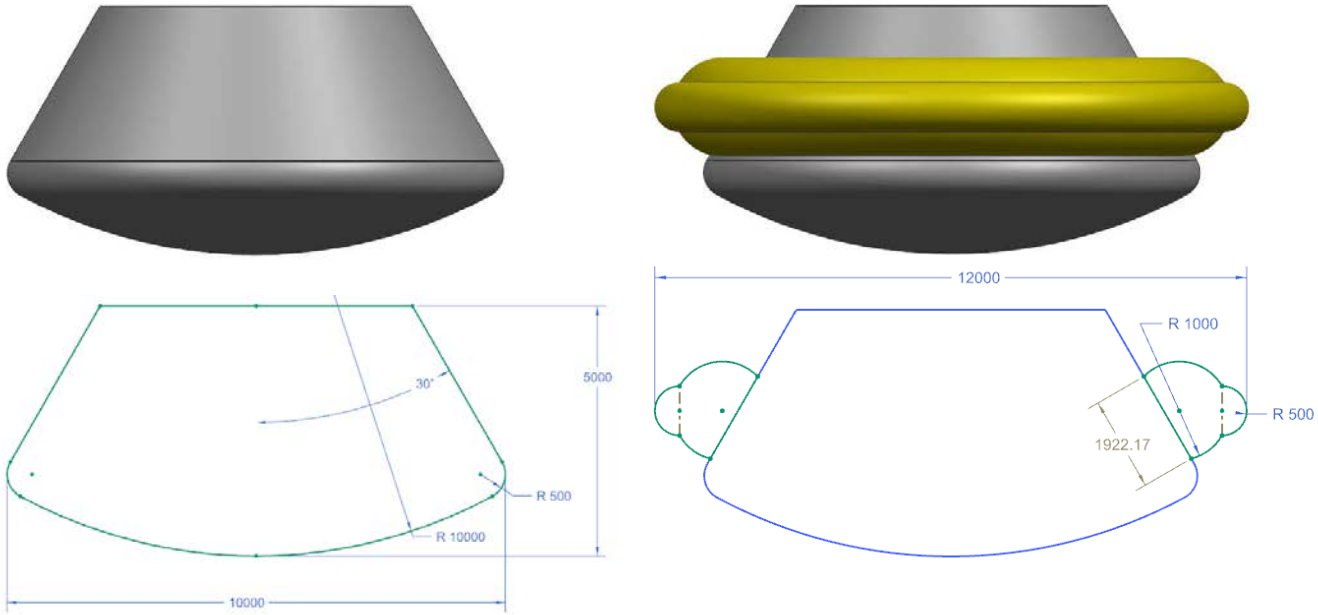
- EDL was simulated with the Dynamics Simulator for Entry, Descent, and Surface landing (DSENDS) software developed at JPL for MSL
- Heatshield geometry used was not optimized, but based on a heritage database
  - 70° sphere-cone similar to previous robotic landers
- Entry phase utilized lift with lift-to-drag (L/D) of 0.24
- Bank-controlled guidance was used for targeting
  - Based on MSL, which was based on Apollo
- SRP was initiated at a point determined by an optimizer for descent guidance logic
  - Backshell jettisoned just prior to SRP initiation
  - Heatshield jettisoned at dynamic pressure of 1 kPa to ensure separation
- At 40 m altitude, engines were throttled down for constant velocity final descent and landing
- Monte Carlo trajectory simulation used sample size of 4,001
  - Uncertainties in atmosphere, winds, aero-database, and mass properties were included

EDL Trajectory for Blunt-Body Lander Concept



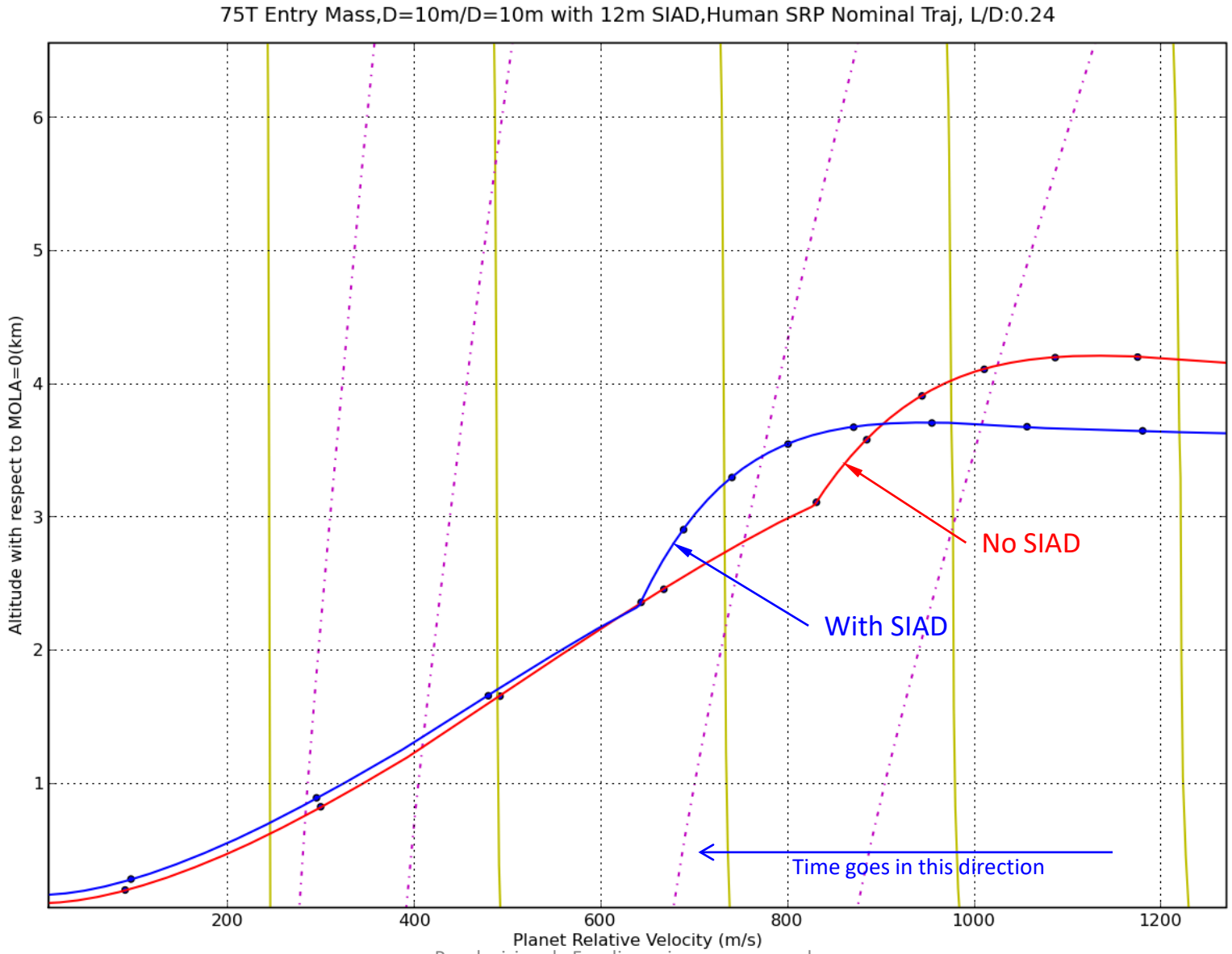
Pre-decisional. For discussion purposes only.

12 m SIAD Based on LDSD



- LSDS SIAD-R was designed to deploy and perform in a supersonic dynamic pressure up to 2.2 kPa at up to Mach 4. The primary limit on this performance envelope is aerothermal heating of the SIAD-R fabric and resulting loss of strength.
- The 12 m SIAD-R has an inflated volume of ~76 m^3, which is 8.4 times the volume of the LDSD SIAD-R inflated volume of 9 m^3.

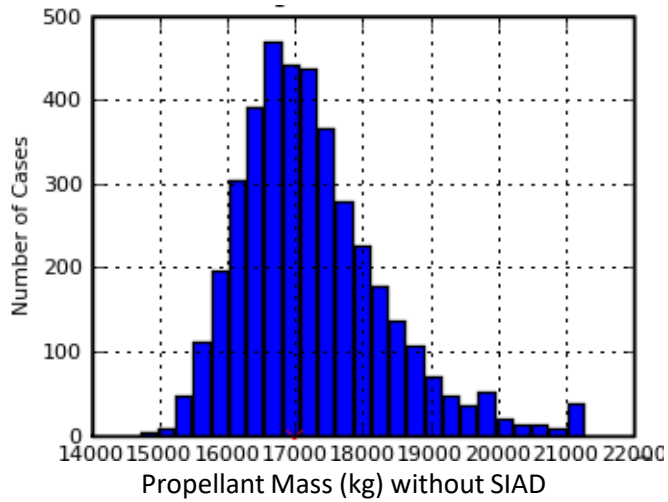
SIAD vs. No SIAD

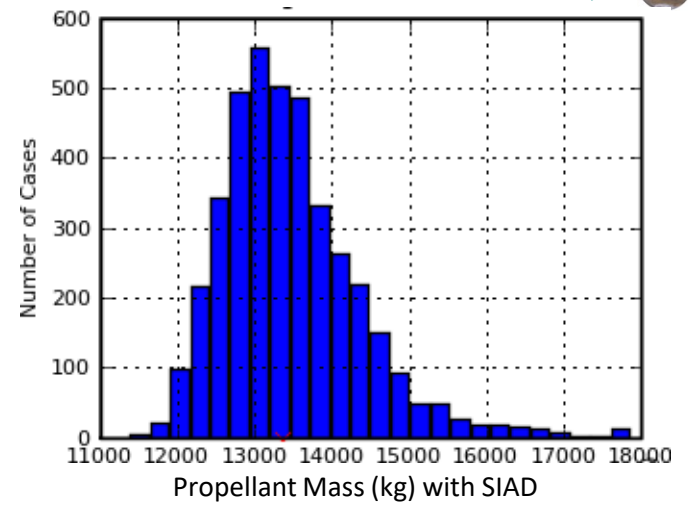


Selected EDL Monte Carlo Results

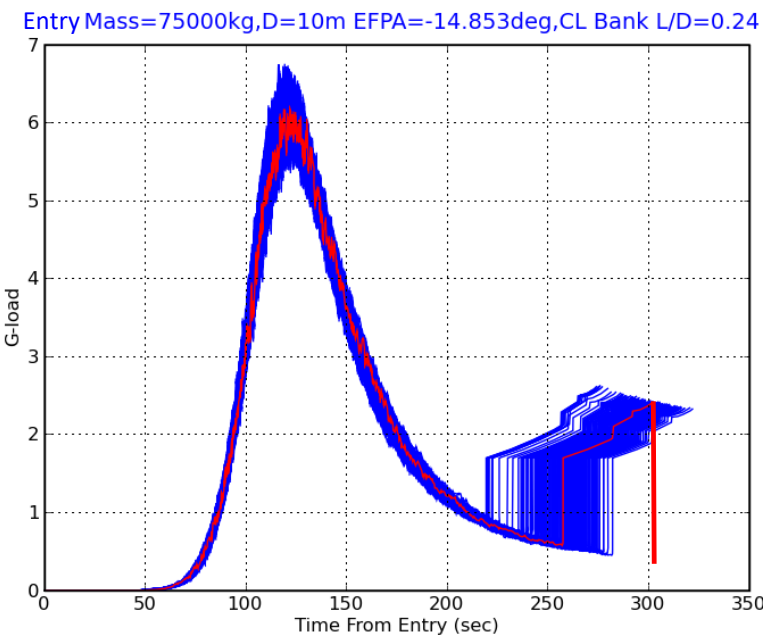
Humans to Mars

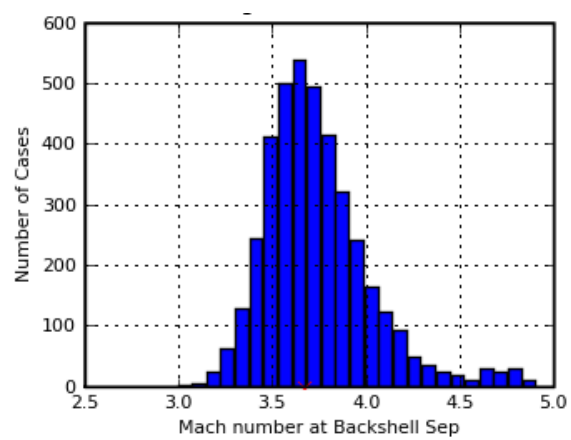
- ~20 t of propellant is used
- Crew experiences ~6.5 g
- Backshell separation and SRP is at ~Mach 3.8 and 4 kPa

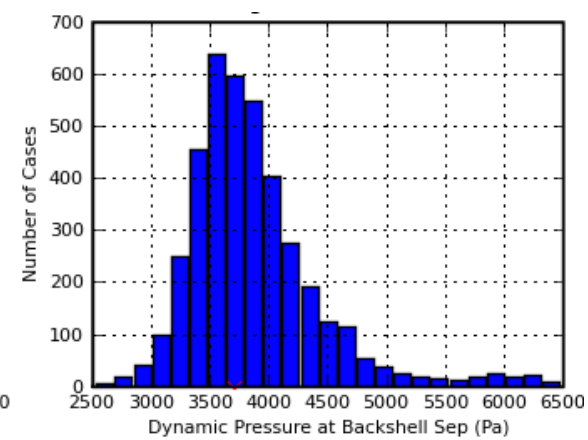




SIAD could save ~4 t of propellant



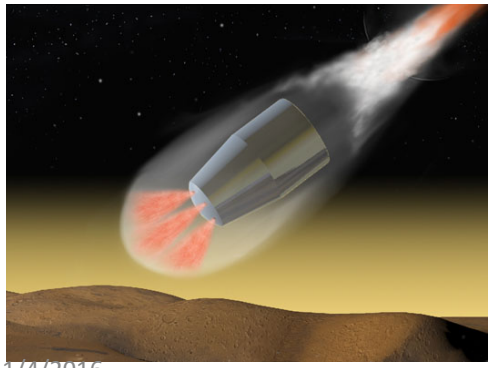


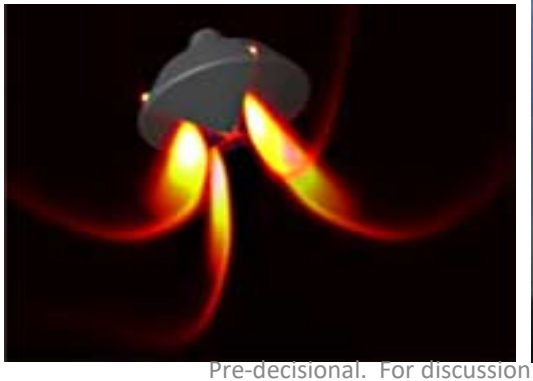


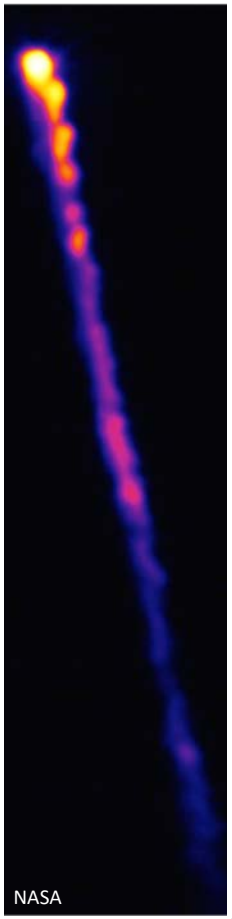
Pre-decisional. For discussion purposes only.

Supersonic Retro-Propulsion (SRP)

- Mars landers to date have used subsonic retro-propulsion
- Analyses have indicated the need for SRP for landing large payloads on Mars
- CFD analysis and wind tunnel tests have been performed, and now SRP data utilizing actual flight data has become available from Space X Falcon 9 stage recovery flights
  - 7 flights have been conducted with a portion of the flight regime being analogous to Mars atmospheric conditions



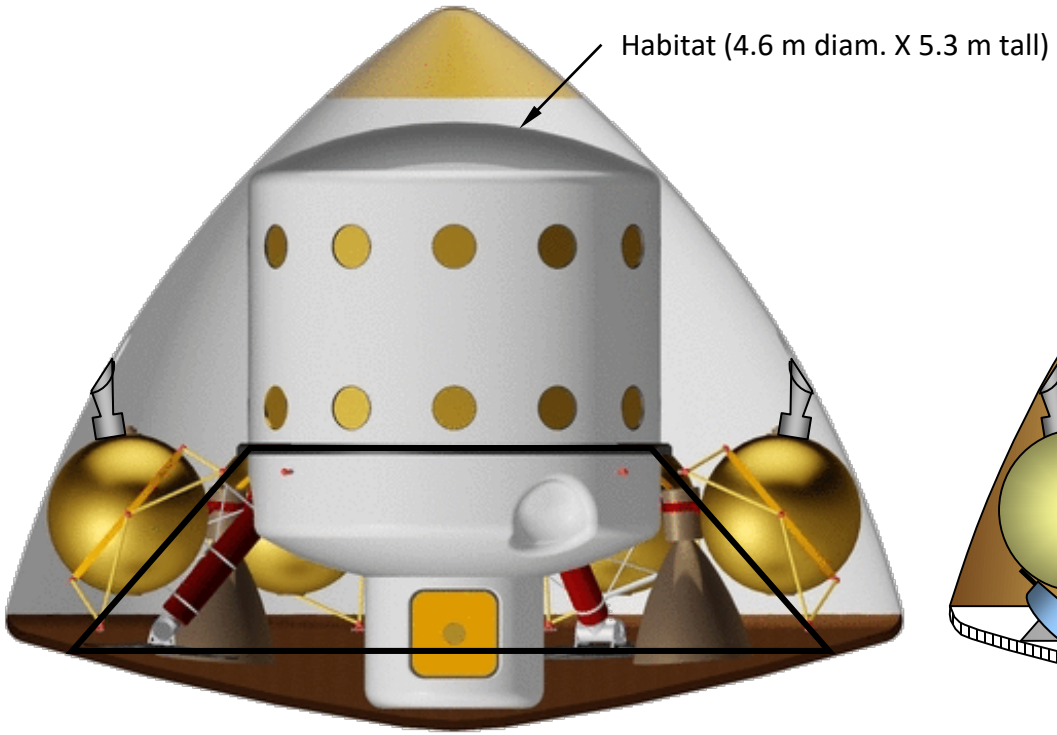


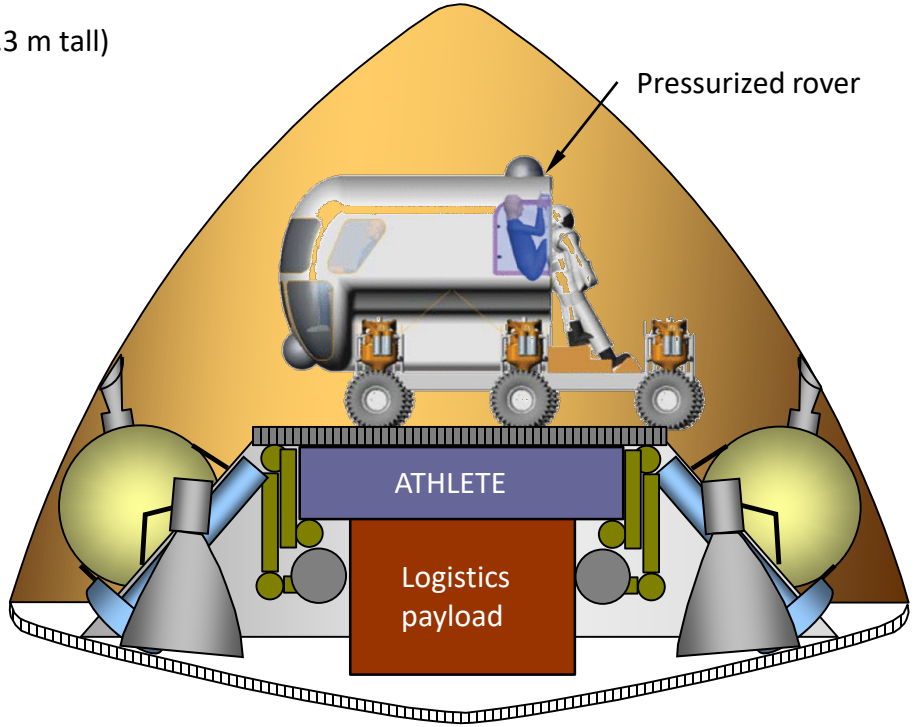


Assumptions for Descent Stage Propulsion

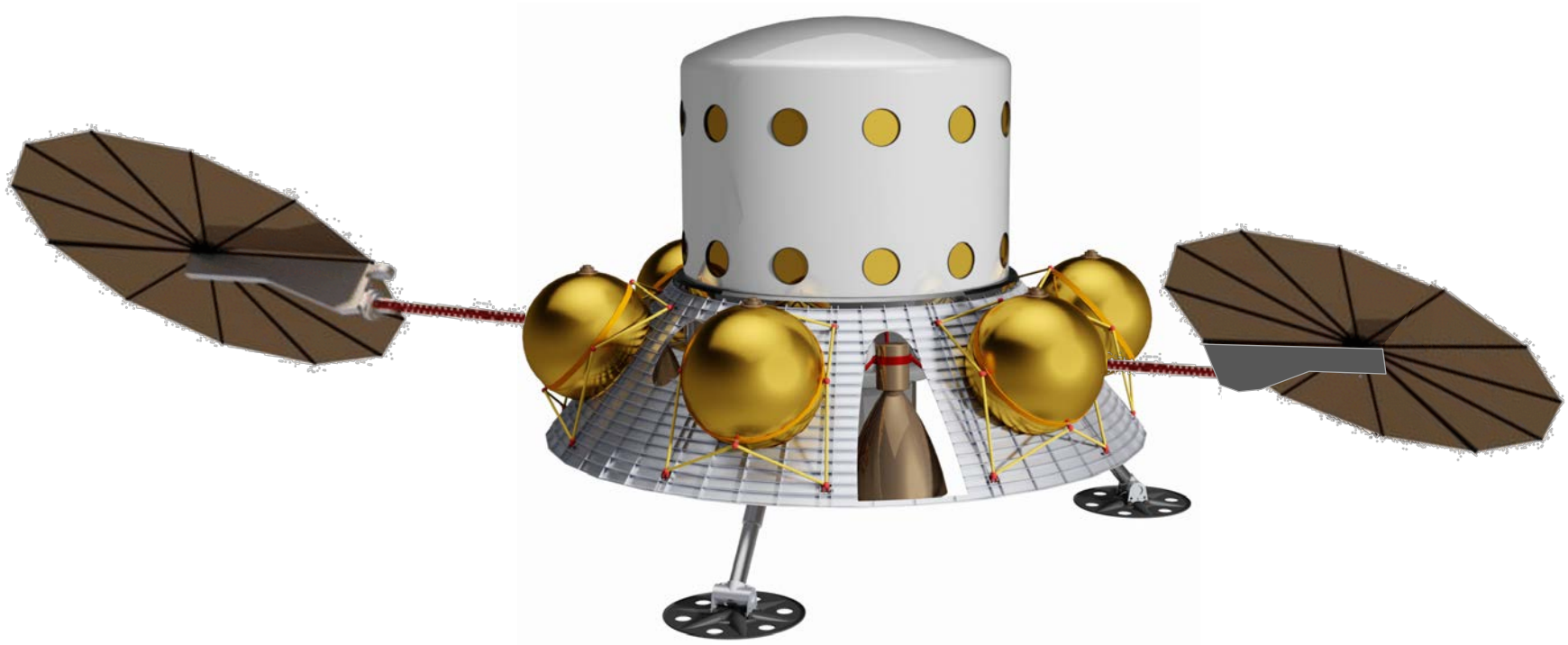
- Pump-fed MMH/MON-25 bipropellant system
  - 6 engines at 250 kN thrust/engine
  - 6 spherical Ti tanks
  - Throttle capability (~12:1 total)
    - Dual injectors (2:1 throttle)
    - Synchronized Engine shutdown (3:1 throttle)
      - 6 engines to 2 engines
    - Engines gimballed ~60° off vertical (2:1 throttle)
      - Reduce soil/surface erosion directly underneath the vehicle
      - Blow debris out and away rather than up
      - Vehicle can be clocked to blow debris in directions away from nearby assets
      - Provide clear downward field of view for sensors
- Pneumatic purge and backflush feature to push holdup in pump and engine assembly back to propellant tank
- Separate RCS biprop thruster system for TCMs, aerocapture periapsis raise, orbit adjustments, de-orbit burn, and EDL 3-axis control

10 m Crewed Mars Lander Cargo Version Concept

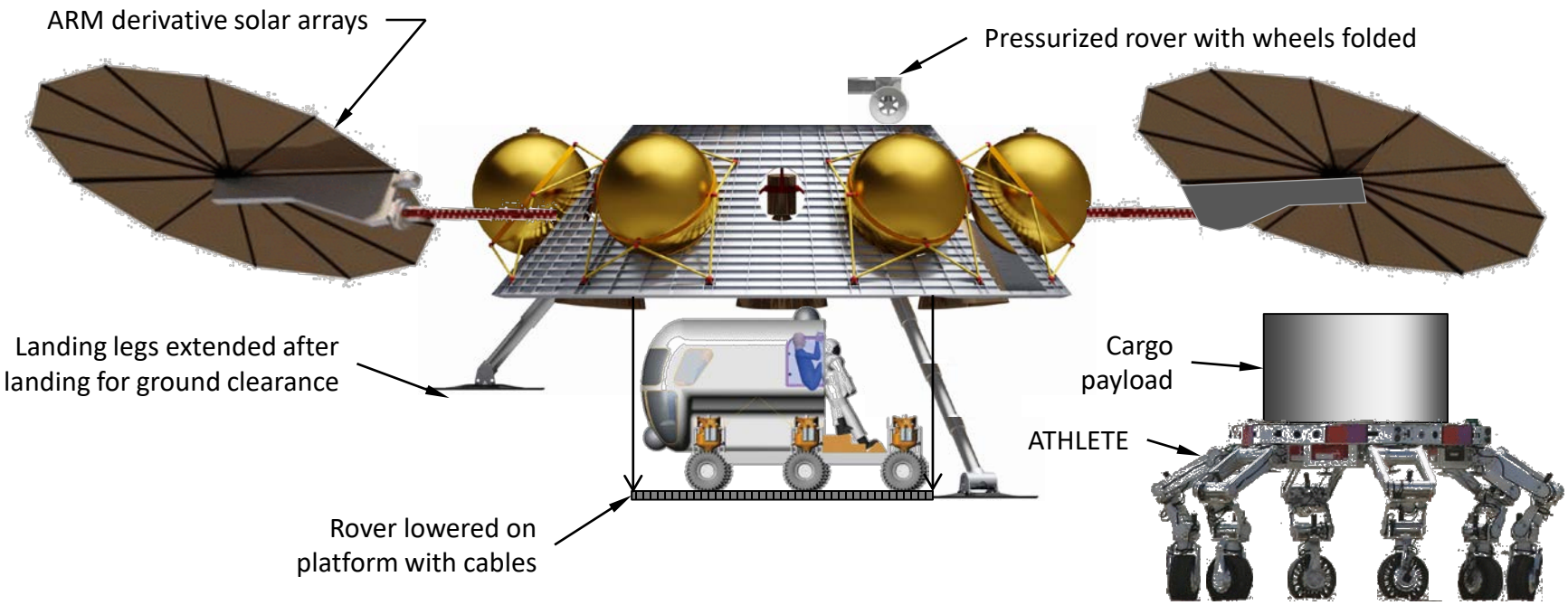




Surface Habitat Concept



Logistics Lander Concept

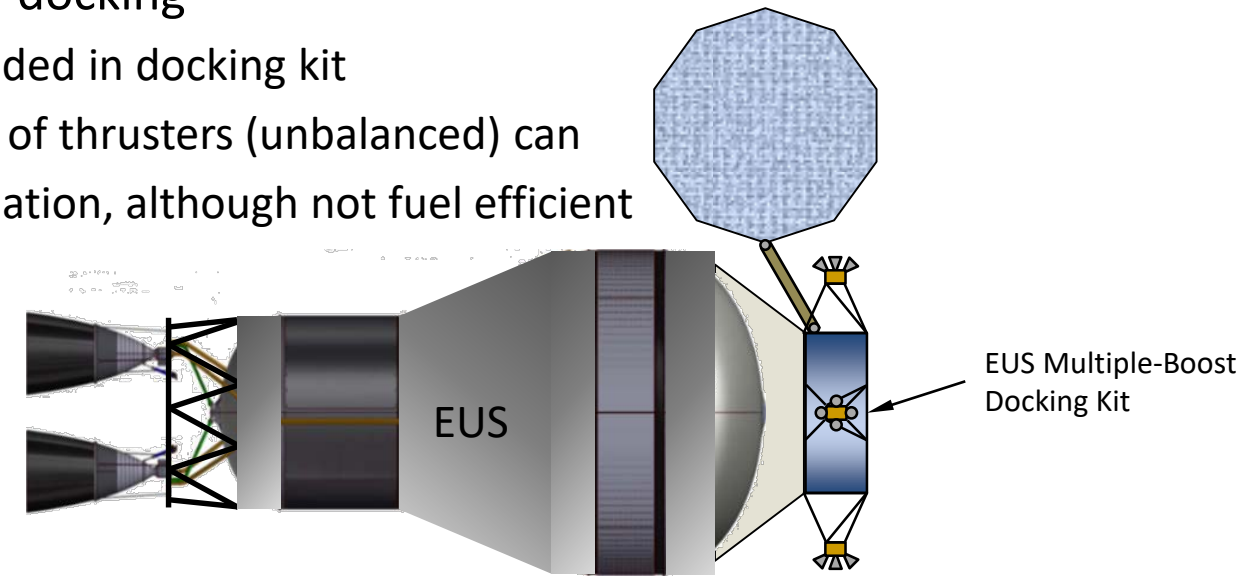


SLS Two-Launch Scenario

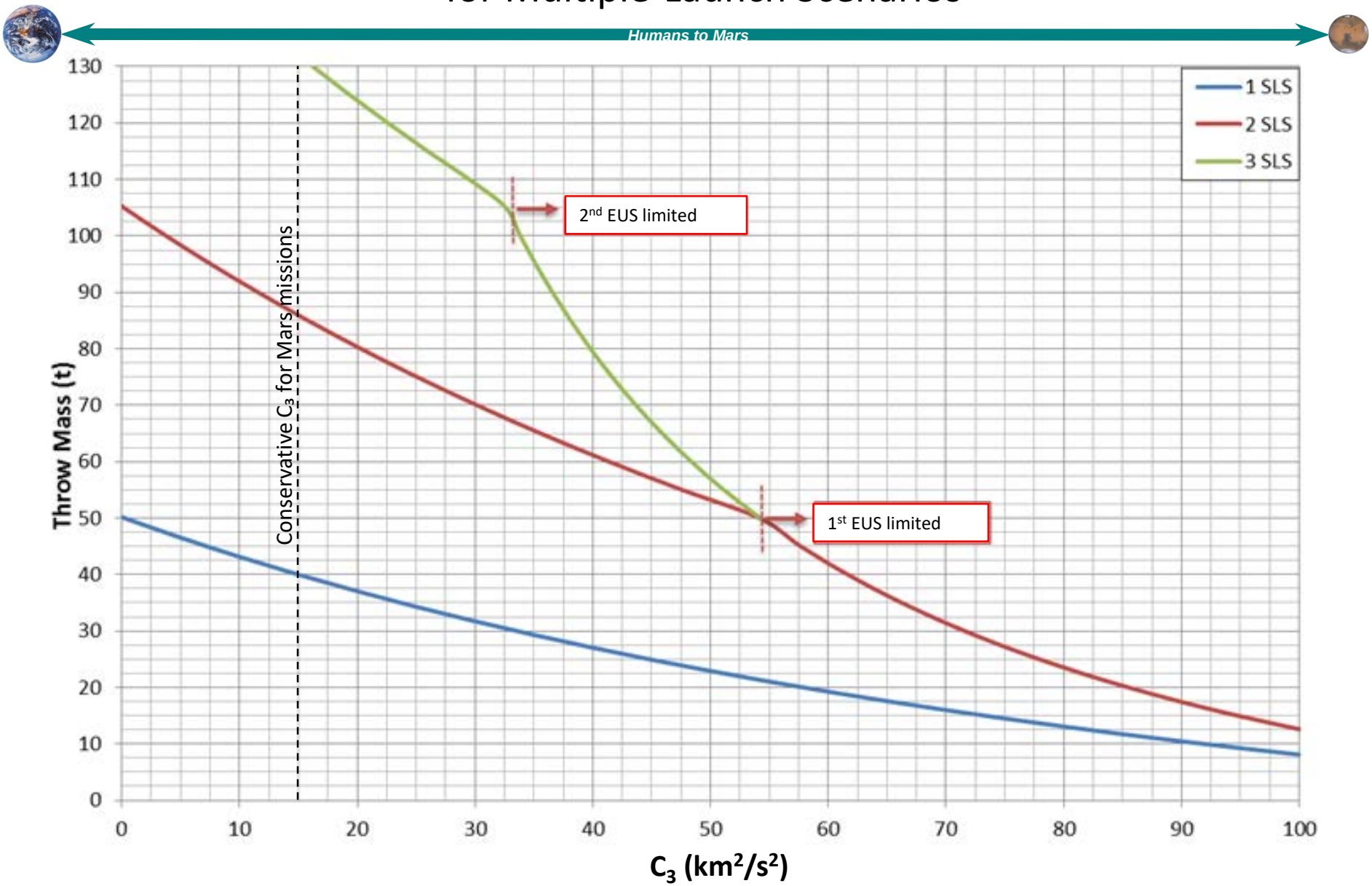
- The first SLS launch would deliver the Mars-bound payload to an elliptical High Earth Orbit (HEO)
  - This launch is flexible and not constrained to a Mars departure window
- The second SLS would be launched with no payload, but it would have a docking kit on the EUS
  - The could be 6 months or more after the 1st launch but is constrained to a conjunction-class Mars departure window
- The EUS from the second SLS would rendezvous and dock with the payload from the first launch
- The EUS would be restarted at perigee to inject the payload to Mars
- This avoids the development and mission cost of a separate Earth Departure Stage

SLS EUS Upgrade for Multiple-Launch Concept

- To enable the two-launch scenario for the SLS Block 2, the EUS would need to be upgraded for the following features:
  - A ~2-day loiter time in Earth orbit
    - Extra insulation and boil-off capability
    - Solar array or LOX/LH_2 fuel cell for extended power
  - Docking ring and semi-autonomous docking capability
    - Could be a kit that is carried like a primary payload
  - RCS thrusters for docking
    - Could be included in docking kit
    - A single plane of thrusters (unbalanced) can perform translation, although not fuel efficient



SLS Block 2 Estimated Performance for Trans-Mars Injection (TMI) for Multiple-Launch Scenarios



Distinguishing Features of this Conceptual Architecture

- Two-SLS launch scenario for lander with no new Earth departure stage required
- Simple blunt body lander with abort to orbit capability for MAV
  - Descent engine failure or off-target landing would not be a loss-of-crew event
- Ogive backshell serves dual purpose as launch fairing
- Low-risk high-heritage non-cryogenic propulsion systems
- MAV delivers crew to LMO to dock with pre-positioned boost stage that provides return to HMO
  - Aerobraking is used to pre-position boost stage in LMO prior to the landing
  - Boost stage provides propulsion and flexibility for orbit phasing

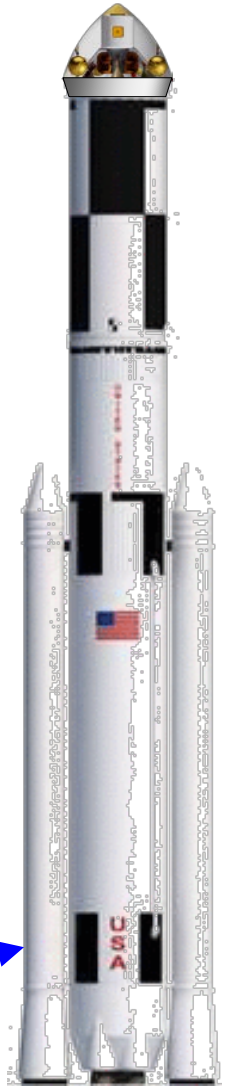
Conclusions

- High TRL design approach appears feasible and could be implemented in the near-term with current industry capabilities
- Sub-scale robotic precursor mission(s) could reduce risk for full-scale development
- This is just an example of a design approach that appears to be feasible
- This is a non-optimized design. Possible improvements could include:
  - Larger diameter heatshield and backshell (e.g. 11 m)
  - Use of larger diameter SIAD or HIAD
  - Higher thrust engines with greater throttling range to reduce gravity losses

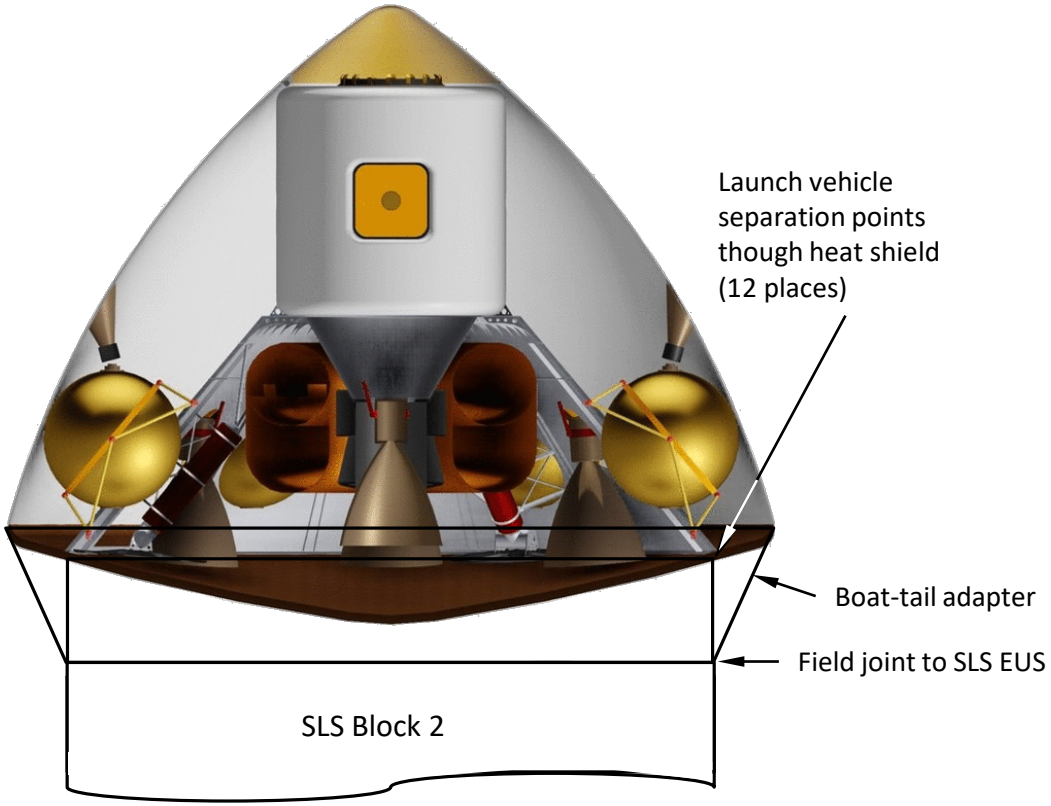
Backup Material

Features of Blunt Body Approach

- It's something we know how to do
  - Experience with Apollo, Viking, MSL, Orion
  - Materials and processes are in place
  - Structural load paths are straightforward
  - Mechanical separations are straightforward (e.g. backshell, heatshield)
  - MSL has demonstrated entry control and steering techniques
- There may be advantages in development cost and schedule
  - Less unknowns, more predictable, simple design
- There are a few new engineering developments required:
  - A ~250 kN human-rated throttleable engine with 325-340 sec I_{SP}
  - Supersonic Retro-Propulsion (SRP)
  - Aerocapture into Mars orbit
    - Might require a second heatshield, which should be straightforward for a blunt body design
    - This was studied for Mars Surveyor 2001
      - Designs and control algorithms were developed
- Diameter of ~10 m would require a hammerhead launch configuration on SLS
  - Lander backshell could potentially double as the payload fairing

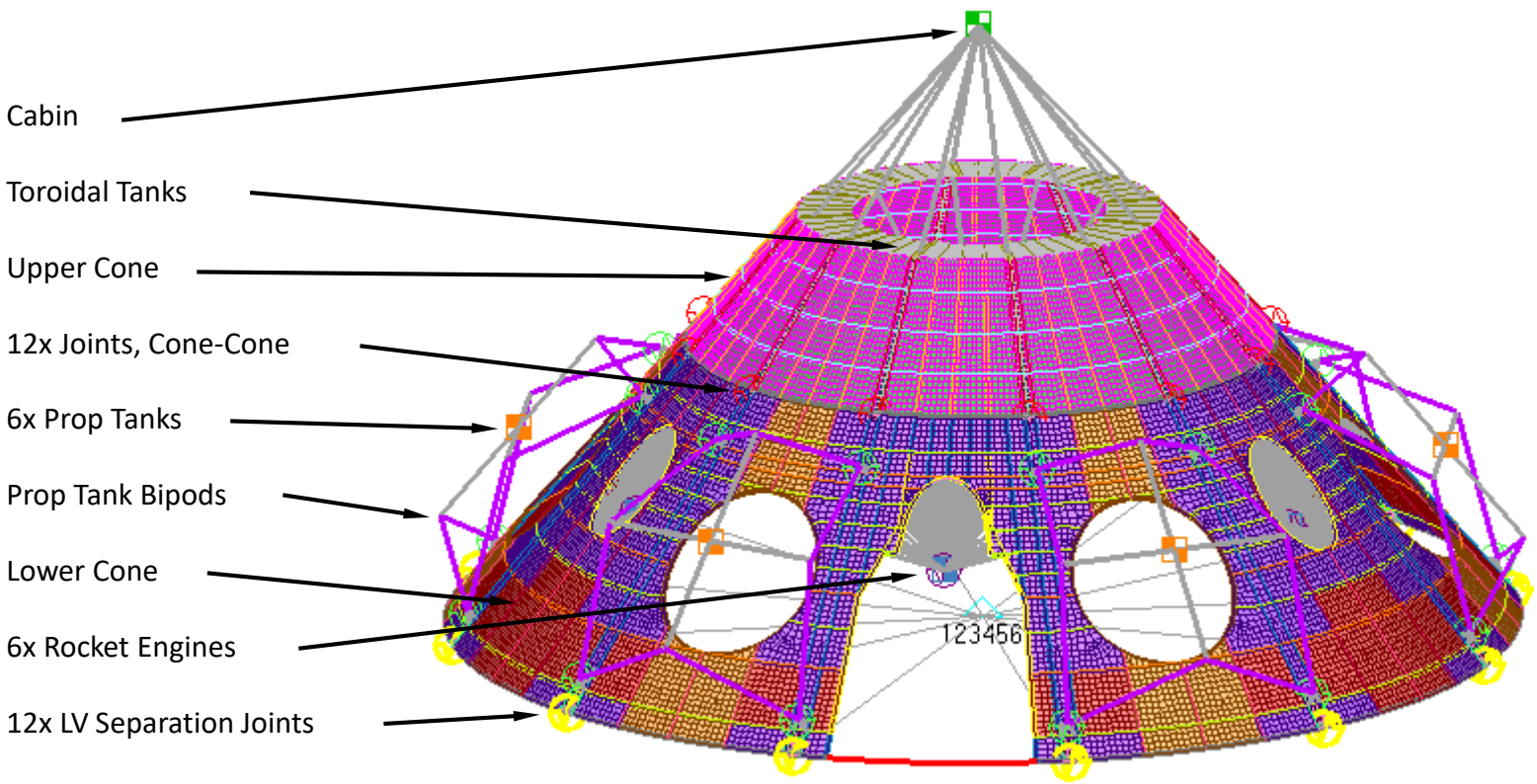


Boat-Tail Adapter to SLS and Load Path

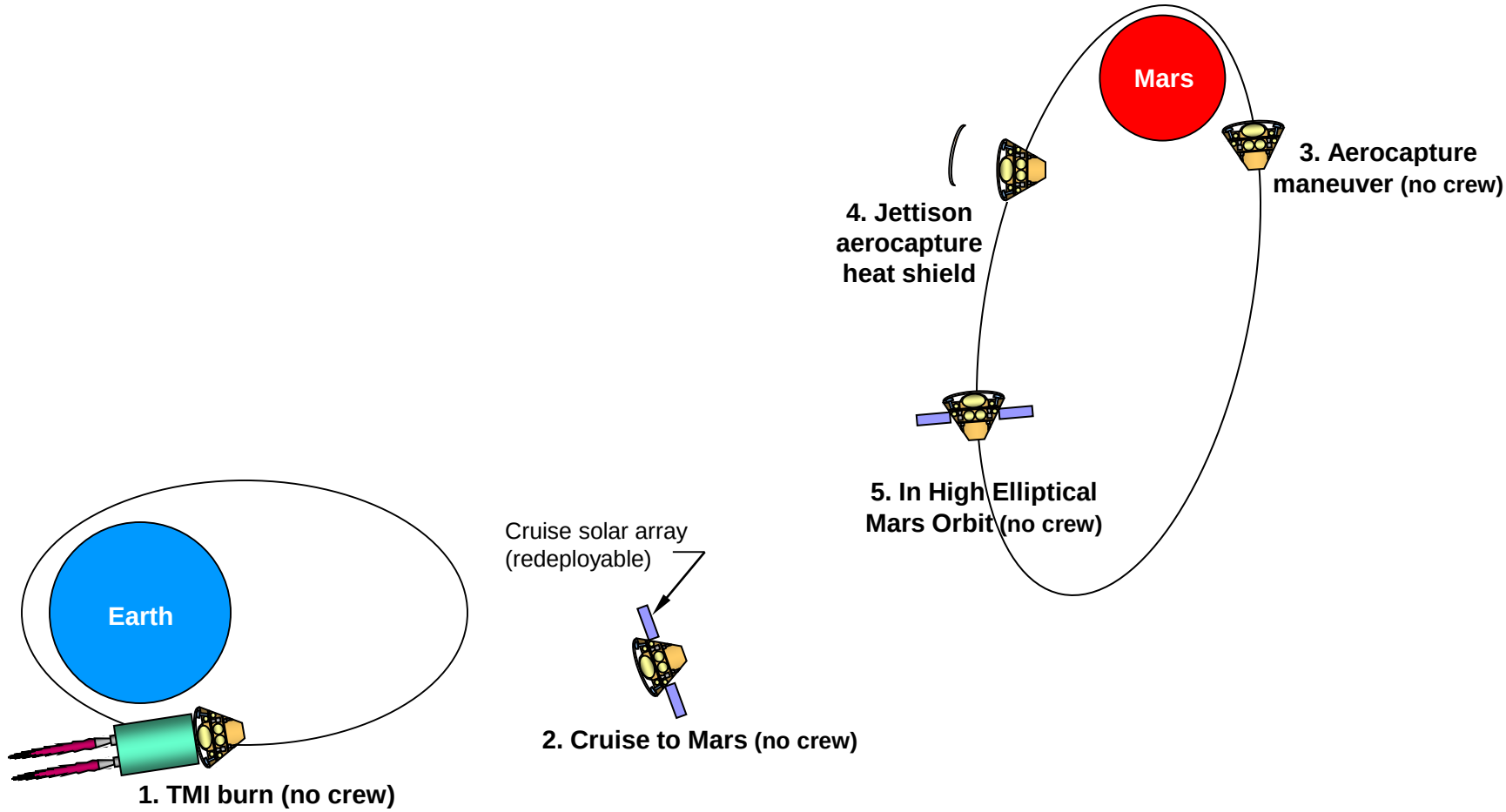


Structural Design and Analysis

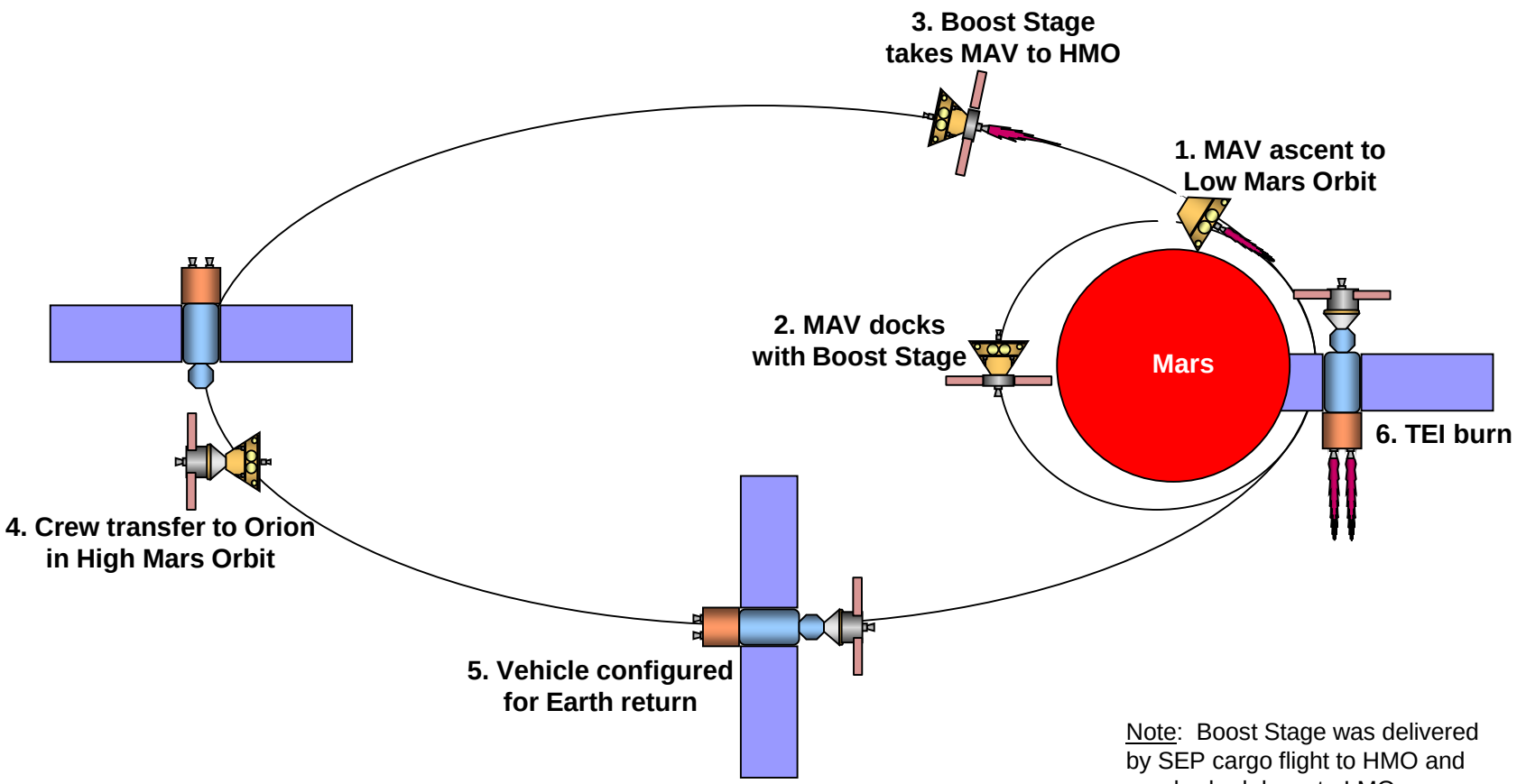
- Monocoque cone with machined ribs; 7000-series Al
- Vehicle lateral 1st mode at 8.5 Hz
- Tank lateral mode at 17.6 Hz



Concept for Descent/Ascent Vehicle (DAV) Transit to High Mars Orbit



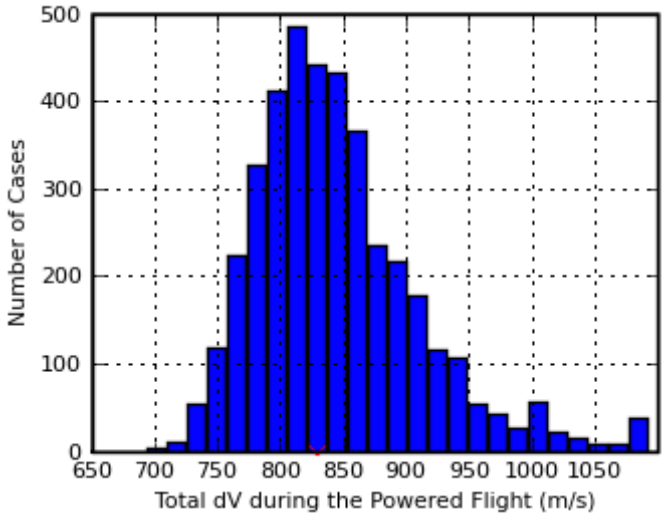
Concept for MAV Ascent, DSH Docking, and Trans-Earth Injection



Note: Boost Stage was delivered by SEP cargo flight to HMO and aerobraked down to LMO.

EDL Propulsive ΔV: SIAD vs. no SIAD

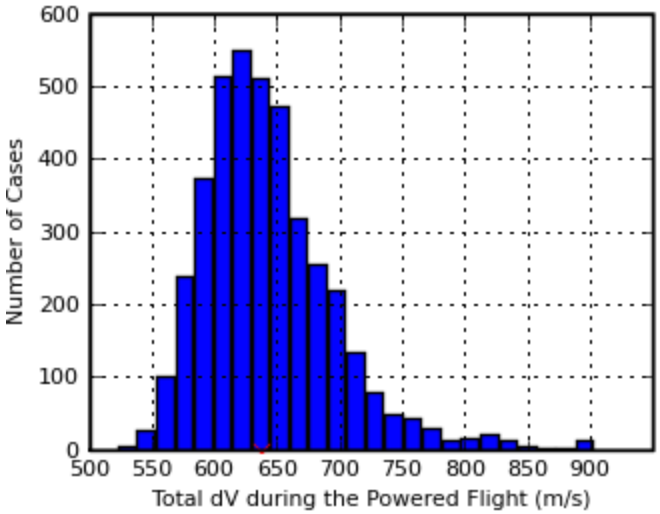
10m Vehicle



Statistics For
Total dV during the Powered Flight (m/s)

Mean = 845.8542
3-sigma = 197.1414
Minimum = 694.4468
05.00 pctile = 759.2625 (1399)
10.00 pctile = 773.5687 (3336)
50.00 pctile = 835.6121 (2714)
80.00 pctile = 892.1808 (2824)
95.00 pctile = 971.2689 (325)
Maximum = 1093.4859
Min Case = 2864
Max Case = 1168

10m Vehicle +12m SIAD



Statistics For
Total dV during the Powered Flight (m/s)

Mean = 643.2093
3-sigma = 158.2525
Minimum = 523.0966
05.00 pctile = 573.7517 (651)
10.00 pctile = 585.7856 (3672)
50.00 pctile = 635.3441 (2501)
80.00 pctile = 679.9650 (93)
95.00 pctile = 737.1890 (1405)
Maximum = 903.5021
Min Case = 2864
Max Case = 2167

Future Evolvability of Lander Concept

- After the initial flights, as technology becomes available, upgrades can be made to the basic lander design:
- Convert MAV to utilize ISRU oxidizer
  - Change to LOX/MON-25 propellants
    - Replace MON-25/MMH engine with high performance LOX/MON-25 engine
    - Tankage modifications to support cryogenic LOX
- Advanced deployable aerodynamic decelerators could be on-ramped, when available, to improve performance