A Minimal Architecture for Human Missions to Mars

An Update

Future In-Space Operations (FISO) Teleconference
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Hoppy Price
John Baker
Firouz Naderi

Jet Propulsion Laboratory
California Institute of Technology

An Input to NASA's Human Space Flight Planning

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- This work provides thoughts on two subjects:
  1. A technical mission architecture, and
  2. What it takes to make that architecture executable

- We hope aspects of this work will be useful to the human space flight planning process

Why Yet Another Mars Architecture?

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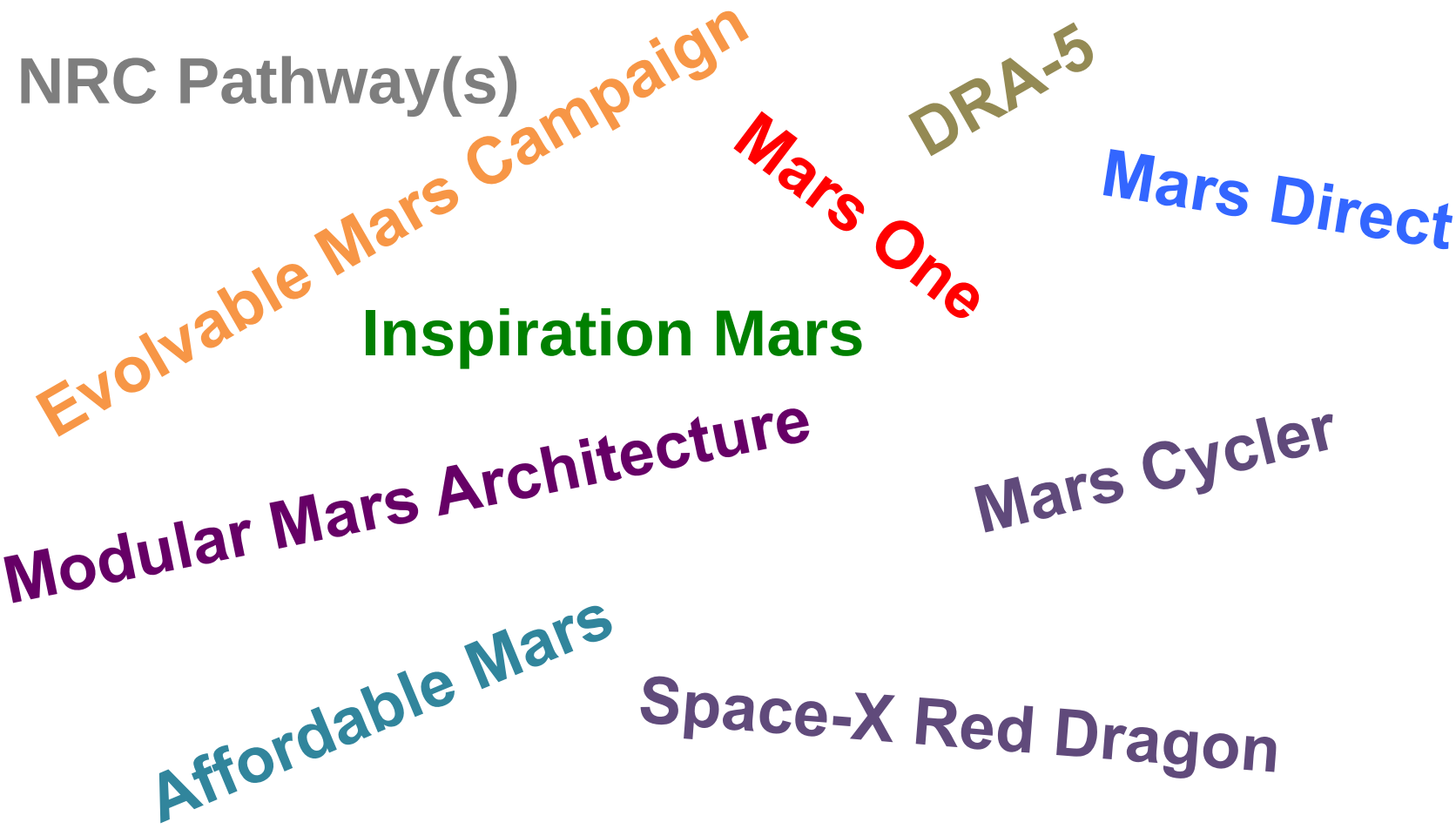

Defining a Multi-decade Executable Program

The Science and the Art

An executable program requires balancing several (sometimes competing) constraints:

- Technical feasibility
- Fiscal affordability
- Stakeholders' interest horizon
- Acceptable risk
- International and private sector engagement
- Political realism across several administrations

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Two Competing Constraints Meet Head on

How Do You Stay Affordable

and yet deliver engaging missions within interest horizon of stakeholders?

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Step-wise introduction of complexity at Mars

1. **Break up the program into phased mission campaigns**
   - **First Campaign**: Mission to the Mars System (land on Phobos)
     - We have proposed *limited* Mars vehicle testing at the Moon/cis-lunar space prior to the first Mars campaign
   - **Second Campaign**: Short Surface Stay on Mars (~1 month)
   - **Third Campaign**: Long Surface Stay on Mars (one year)
   - **Continuing Missions**: Move toward a permanent presence
     - Each mission builds on the infrastructure from the previous mission
     - On-ramp new technologies (e.g. ISRU, food production) over time
2. **Minimal Architecture**
   - Rely on the set of elements already under development by NASA (SLS, Orion, DSH, SEP) and avoid complex new developments (such as nuclear fission surface power and ISRU) where possible

To spread the cost (required cash flow) and the risk, break up the challenges of crewed travel to Mars into **two** separate campaigns

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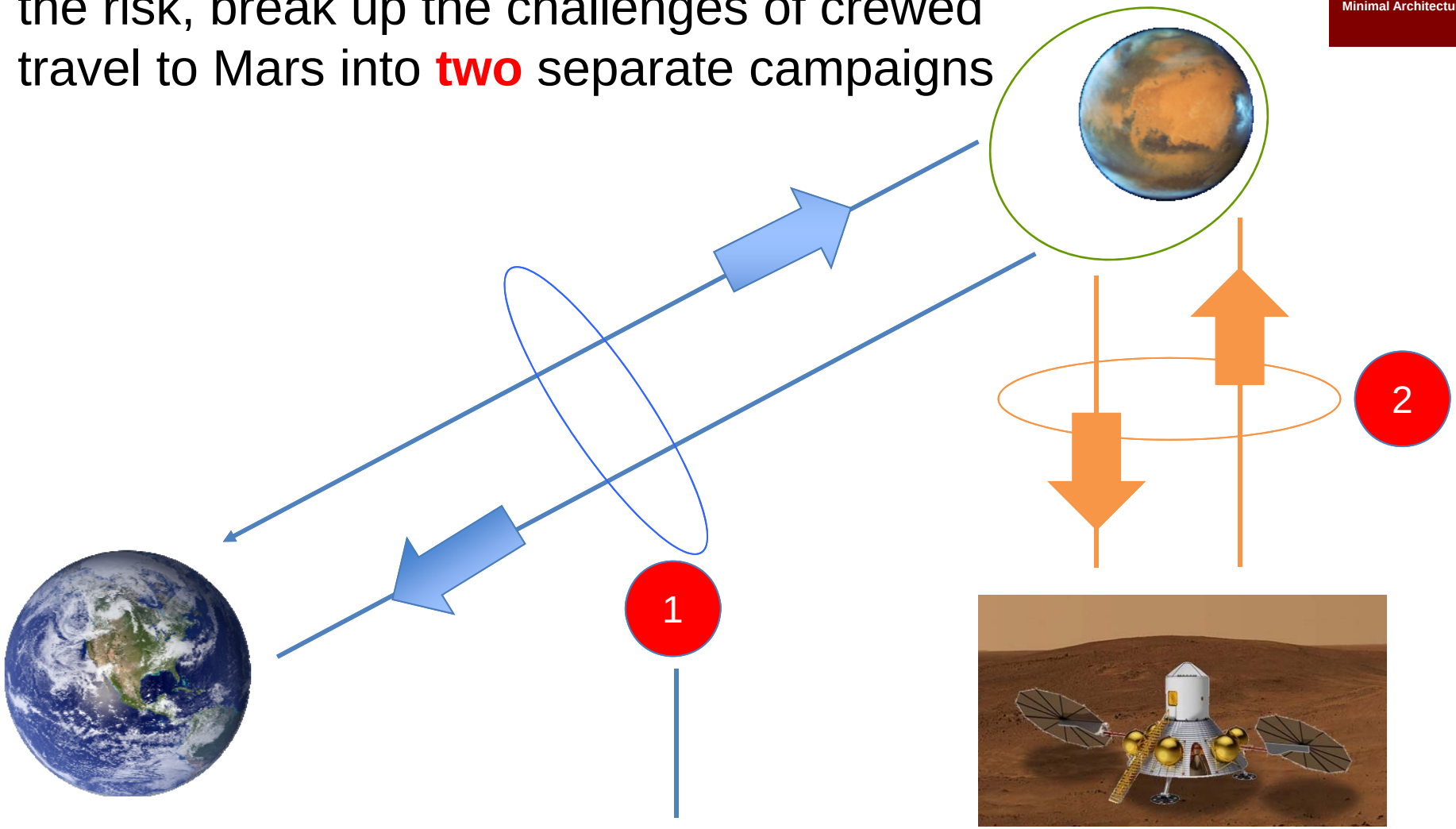

Challenges of Round Trip Travel to Mars Orbit

Challenges of Landing and Taking Off From Mars with Crew

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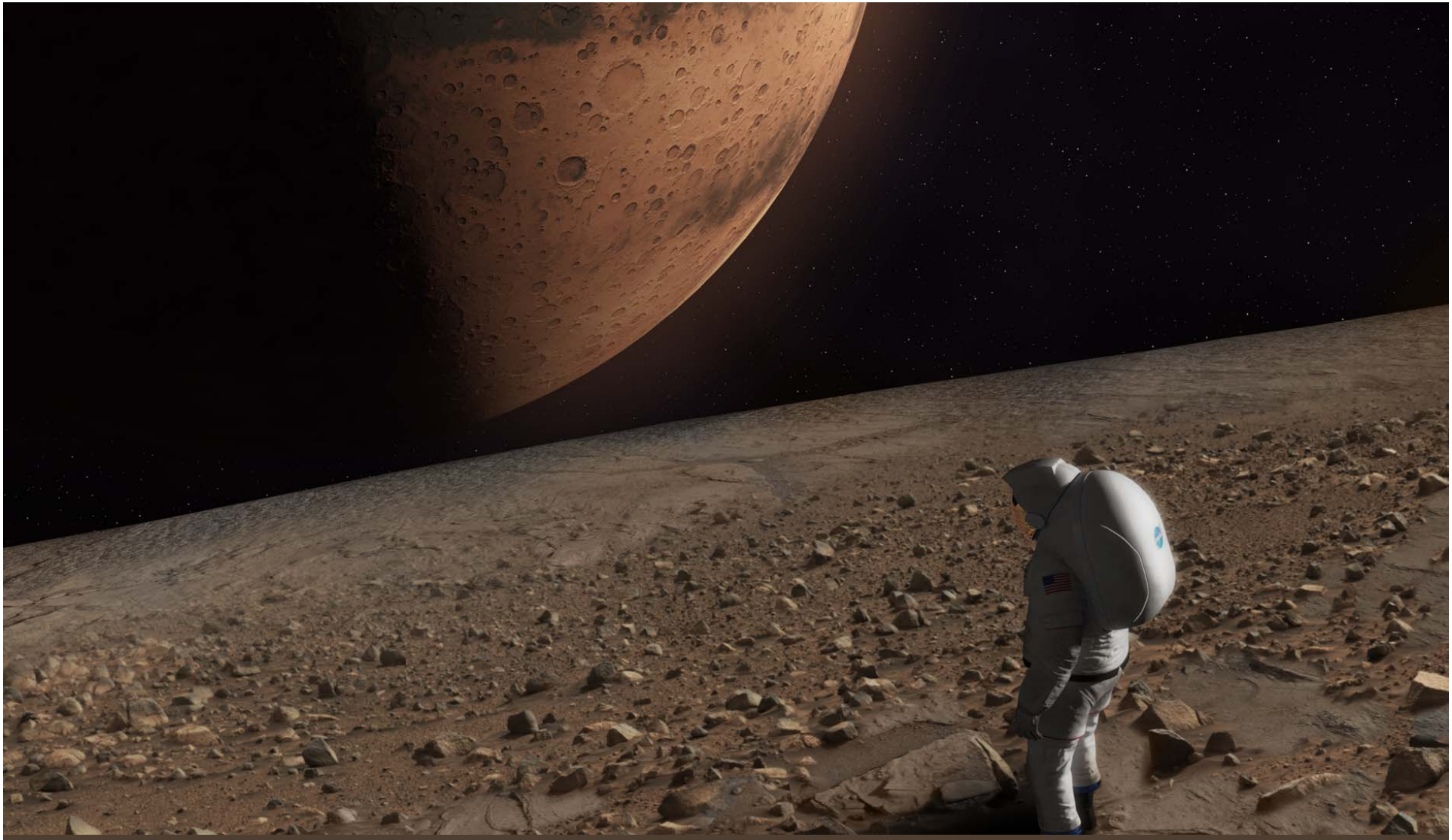
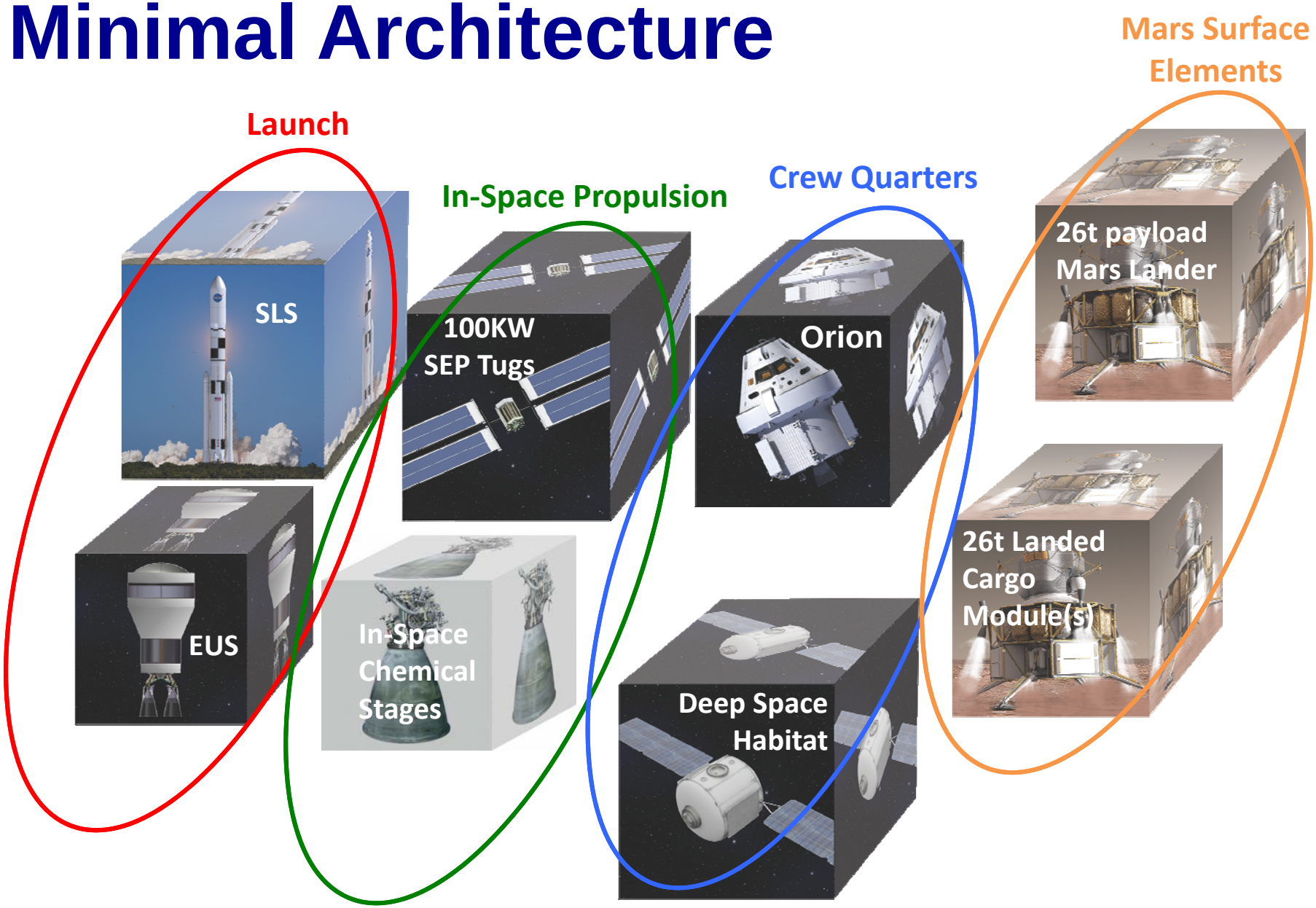


Mars as Seen from Phobos

Building Blocks of a Minimal Architecture



Increasing the Likelihood that it Can be Implemented

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- Mission architectures need to be checked for **affordability**
  - Mission costs need to be verified by a non-advocate third party
- For the Journey to Mars to remain in the **interest horizon** of stakeholders, humans need to get to the Mars system in the early 2030's
- Much can be learned from ISS in the next decade, but NASA needs to plan for the **ISS end game** and repurposing those funds
- Gaining Experience at the **Moon/cis-lunar space** can be beneficial; however, the extent of activities should be weighed against any delays in the time table for human presence at Mars
- A coherent **long-term strategy** (beyond the 5-year budget cycle) needs to be articulated
  - Engage potential international partners
  - Outline opportunities for private sector participation
  - Keep other stake holders interested

Mission to Mars Orbit and Phobos

Phobos Landing Concept

Attributes of the campaign

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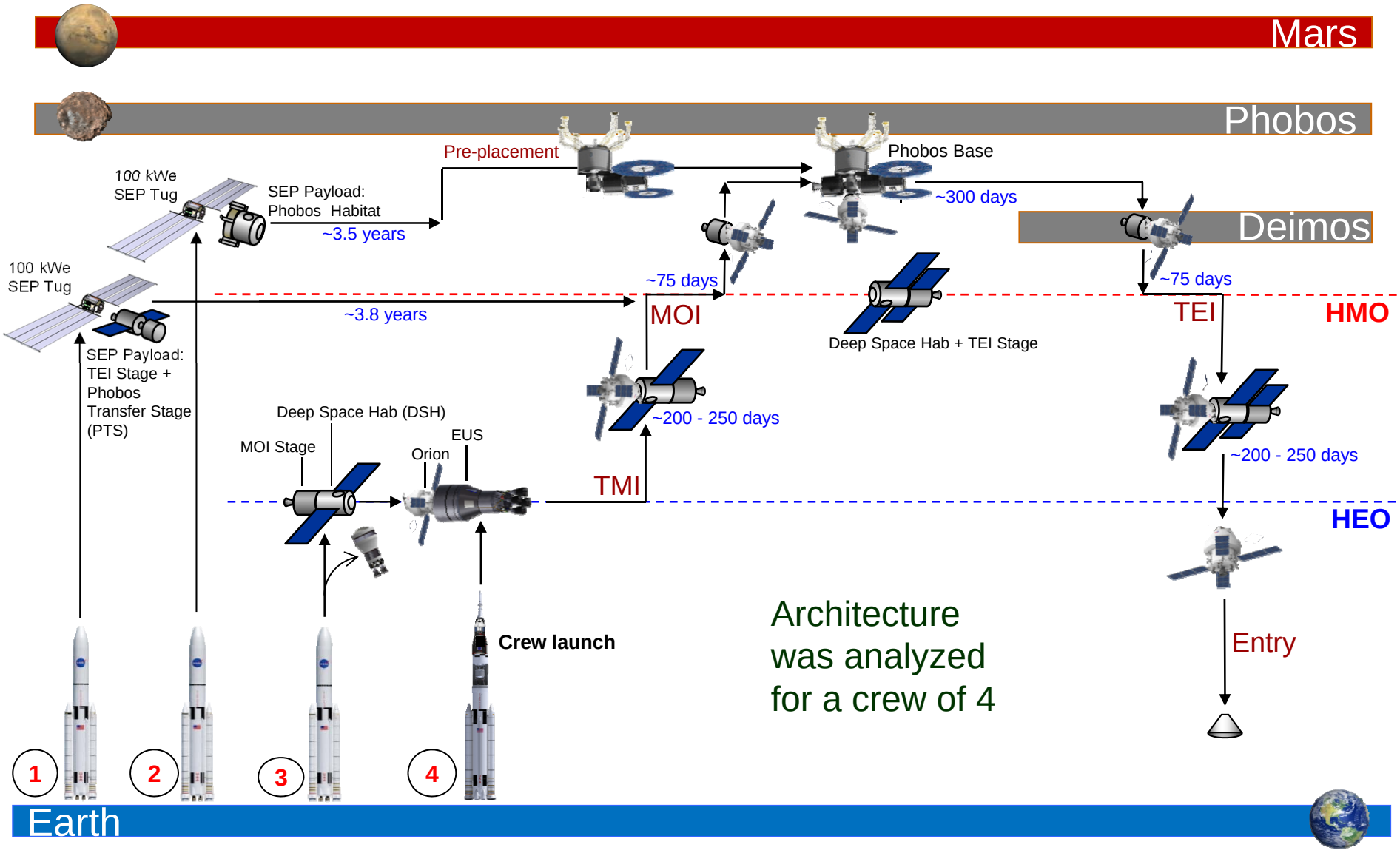
- Precursor to Mars landing campaign
- Proves out method for getting to Mars orbit and back
- Uses 4 SLS launches
- Pre-position assets in Mars system with SEP tugs prior to crew arrival
- Round trip crew mission ~2 ½ years; ~300 days at Phobos

Phobos Mission Concept

4 SLS Launches



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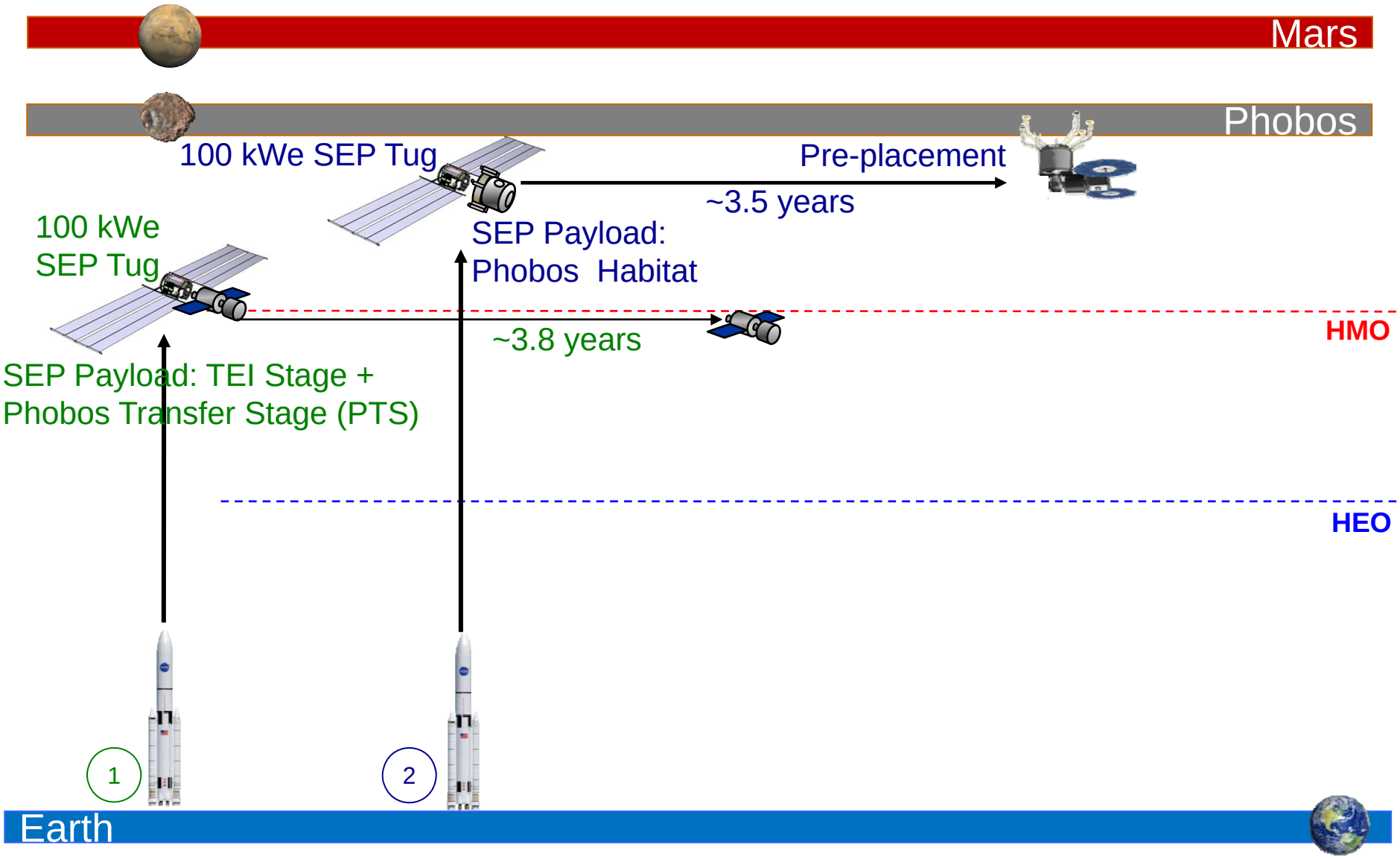
Getting Cargo to HMO and Phobos



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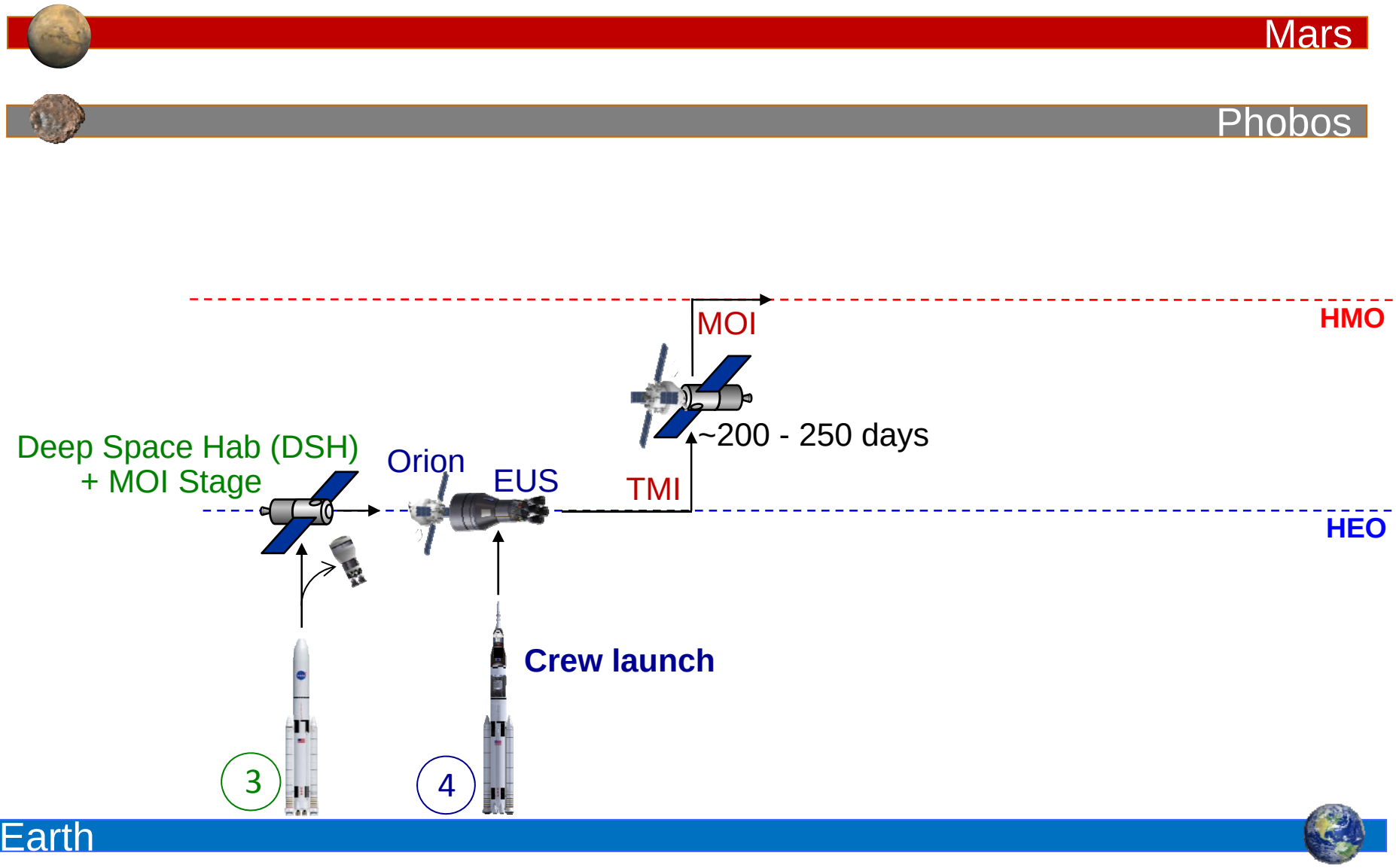
Getting Crew to HMO



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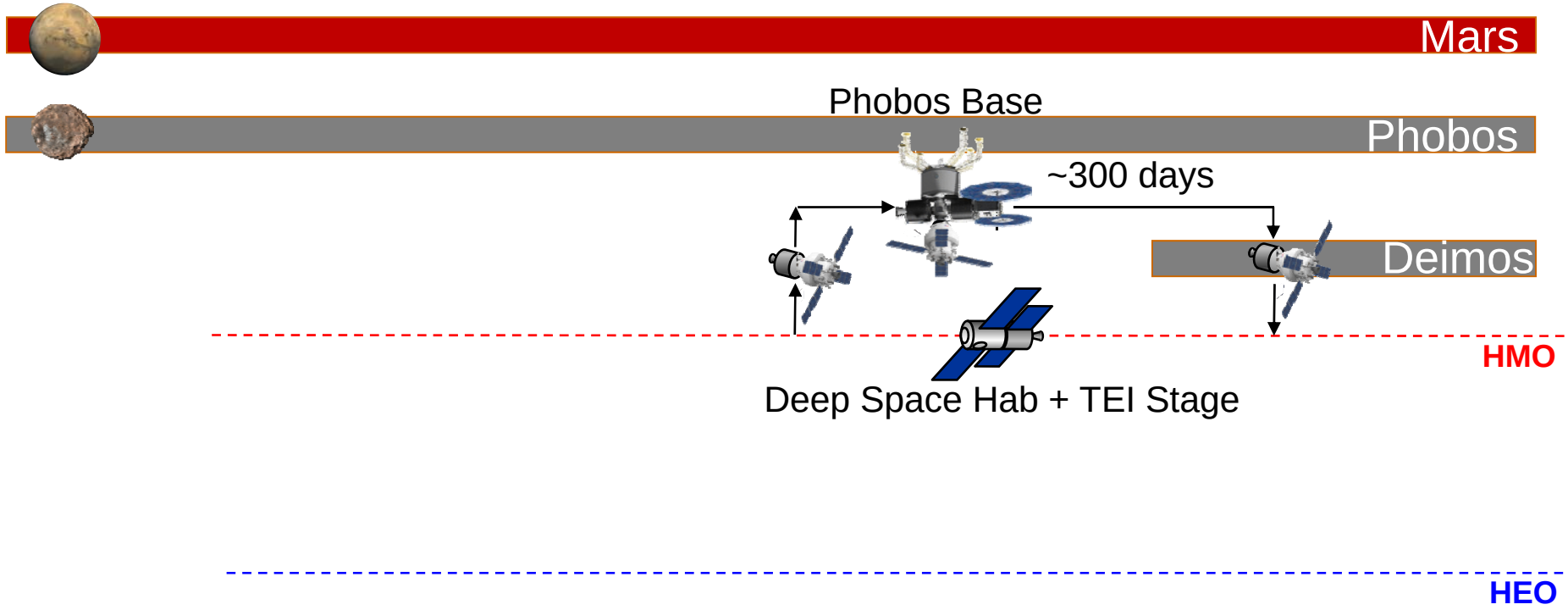
Getting Crew from HMO to Phobos and Back to HMO



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Phobos Base Concept

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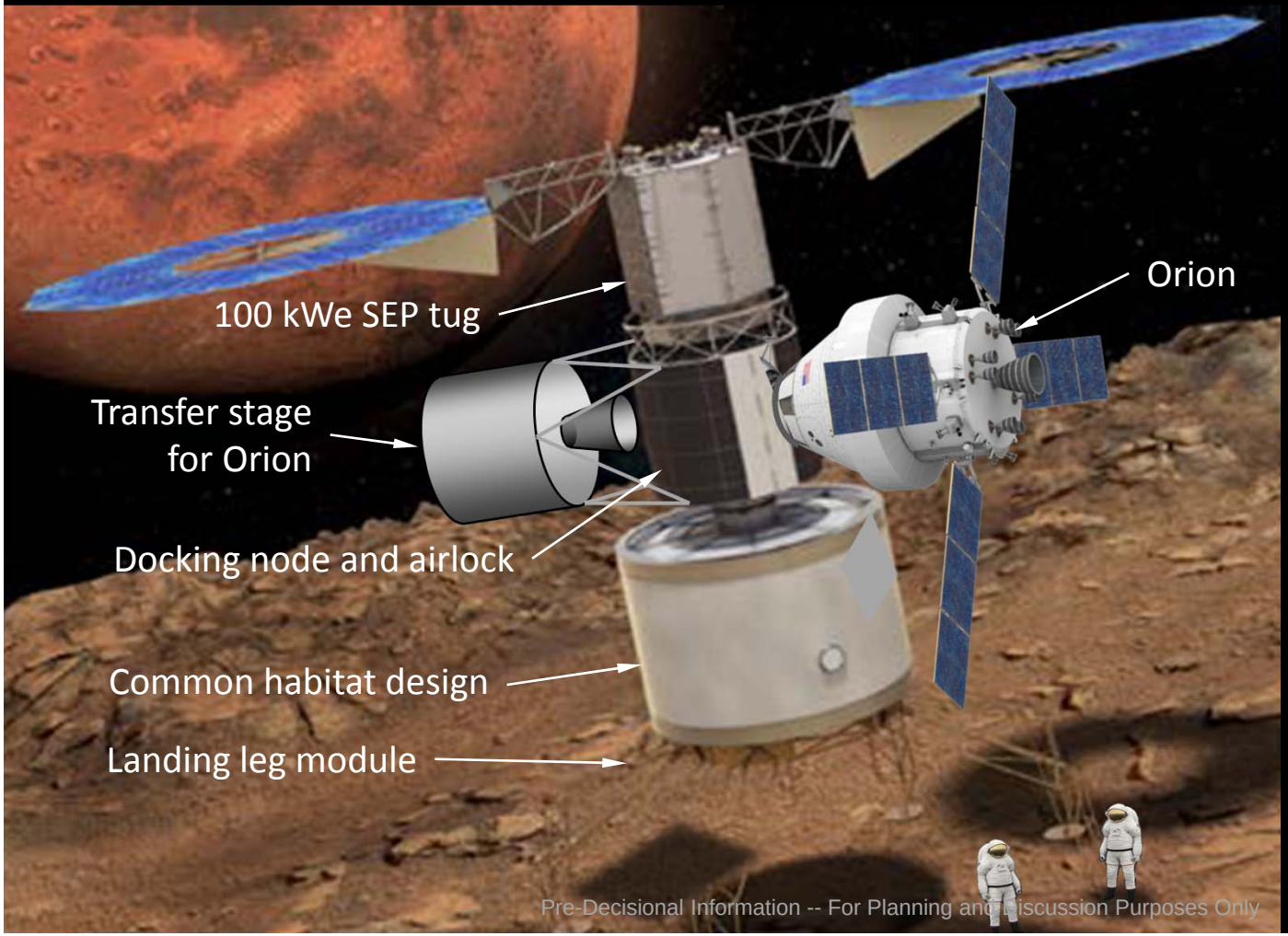

- Supports a crew of 4
- Could be relocated to different sites
- Could be re-used by future crews

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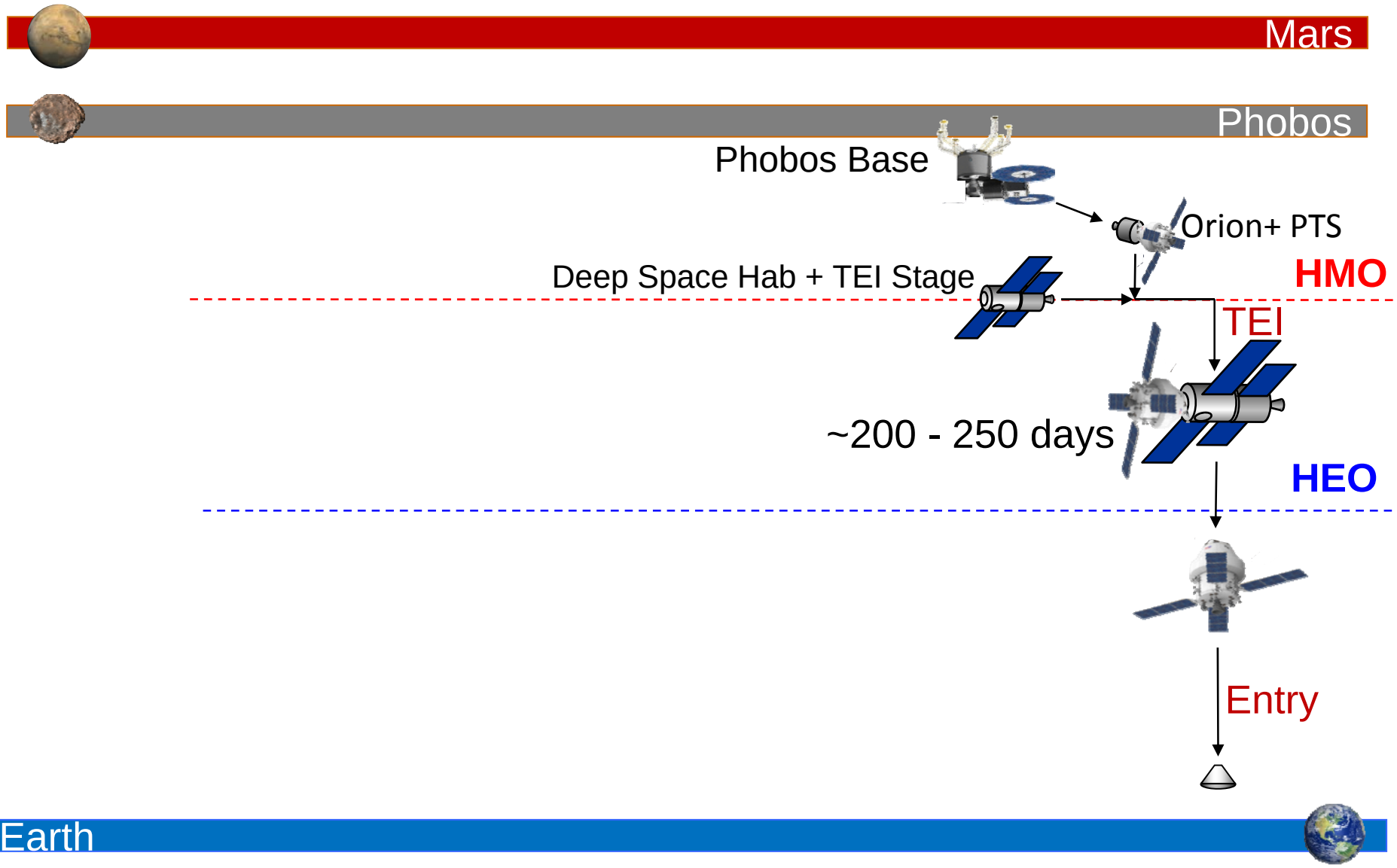
Coming Back to Earth



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Mars Short Surface Stay Campaign

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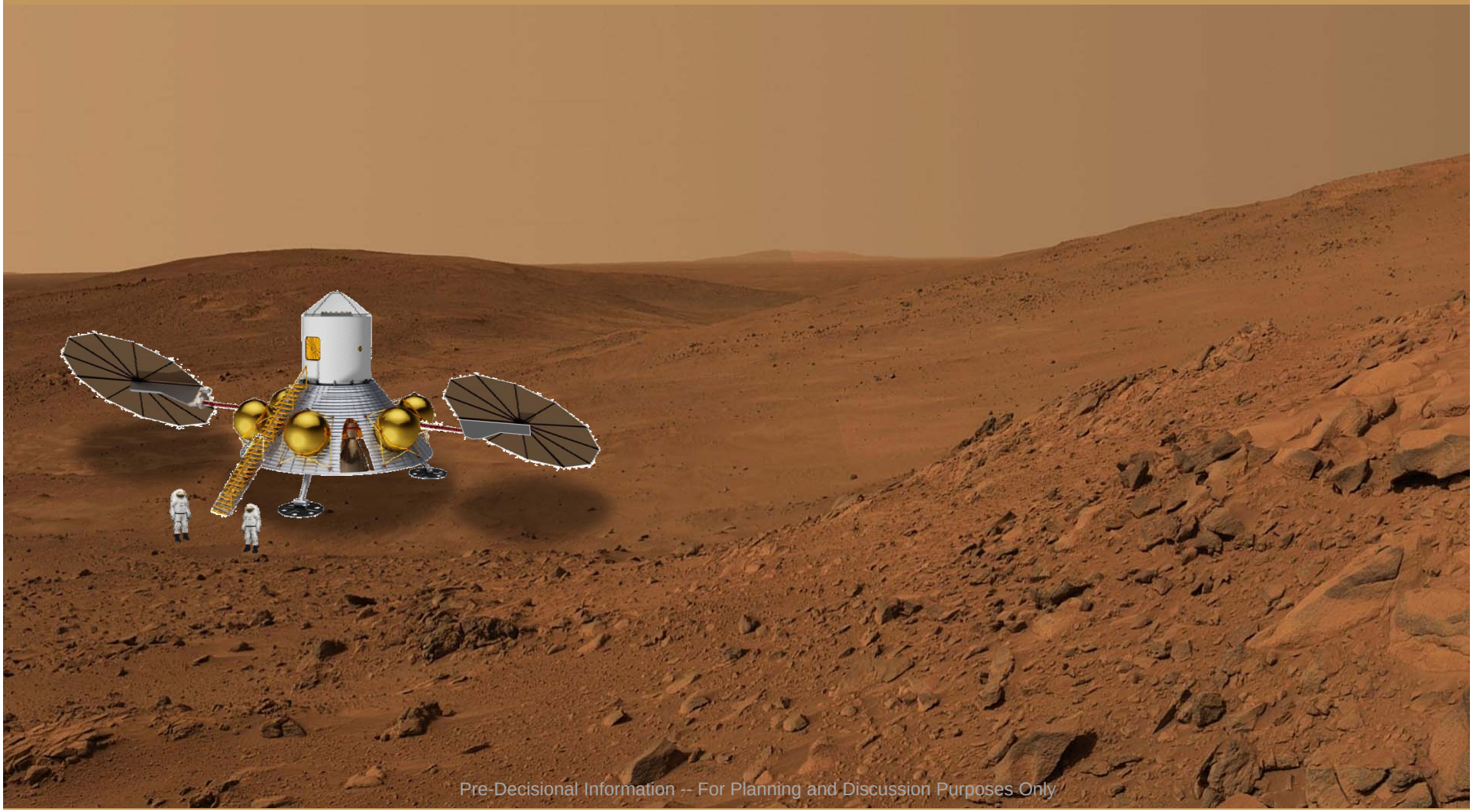

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One Month Mars Surface Stay

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Attributes of the Campaign

- Architecture re-uses the Phobos approach for getting crew to HMO and back to Earth (already tested in 2033)
- The lander requires 2 additional SLS launches relative to Phobos mission, bringing total SLS launches to 6
  - Lander entry mass ~75t with 26 t useful landed mass
  - Crew of 4 to the surface for ~1 month stay
  - Can utilize cargo lander sent to support the 2nd surface mission
- Return from Mars surface is achieved through a two-step ascent to High Mars Orbit (HMO)
  - MAV takes crew from surface to Low Mars Orbit (LMO)
  - Then boost stage takes crew in MAV to High Mars Orbit (HMO)
  - This minimizes MAV propellant load and enables 26 t lander
- This is a pathfinder for following missions which will have >1 Earth year stay on the Martian surface

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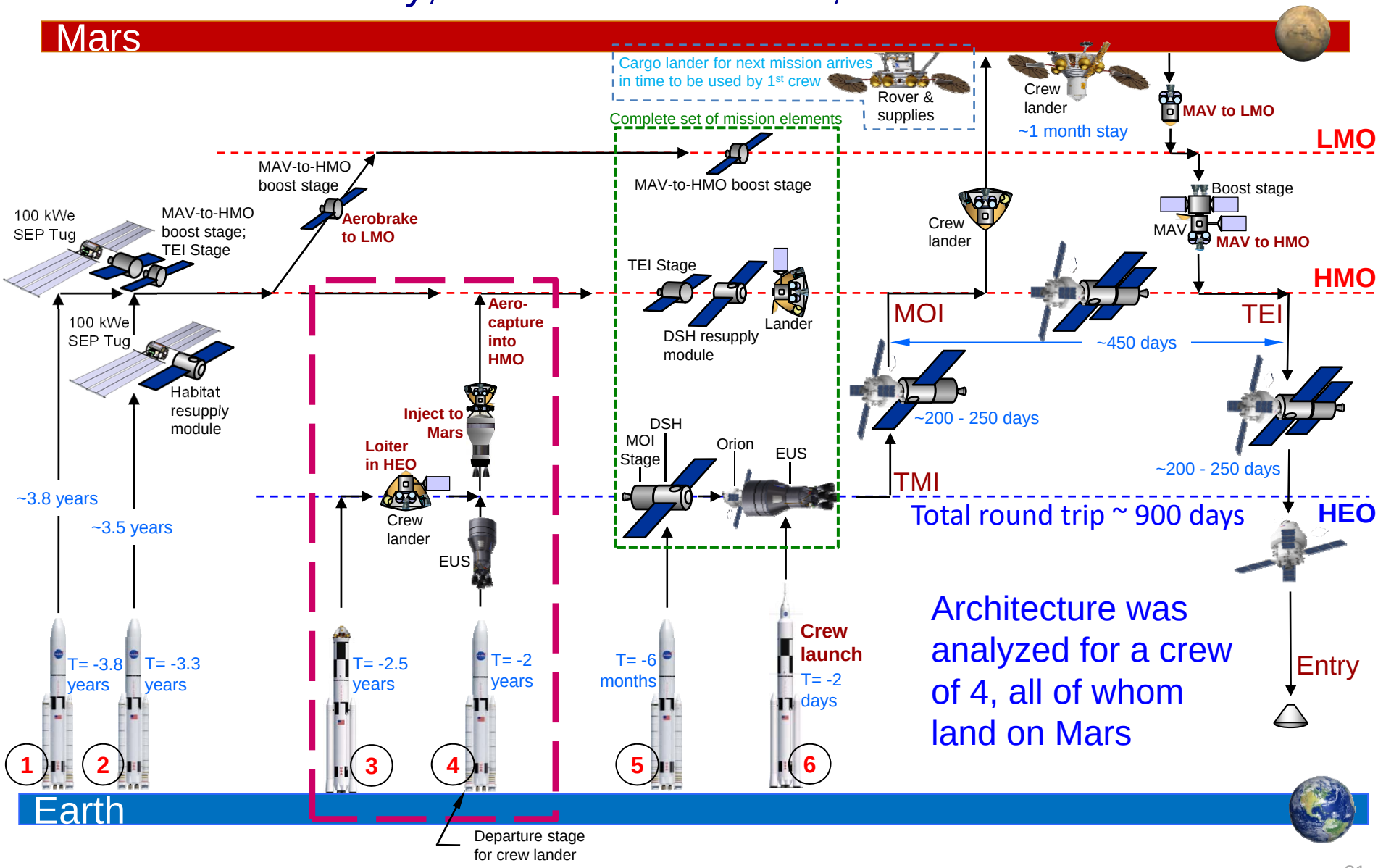
Short Surface Stay Concept

1 month surface stay; Crew of 4 to surface; 6 SLS launches



Architecture was analyzed for a crew of 4, all of whom land on Mars

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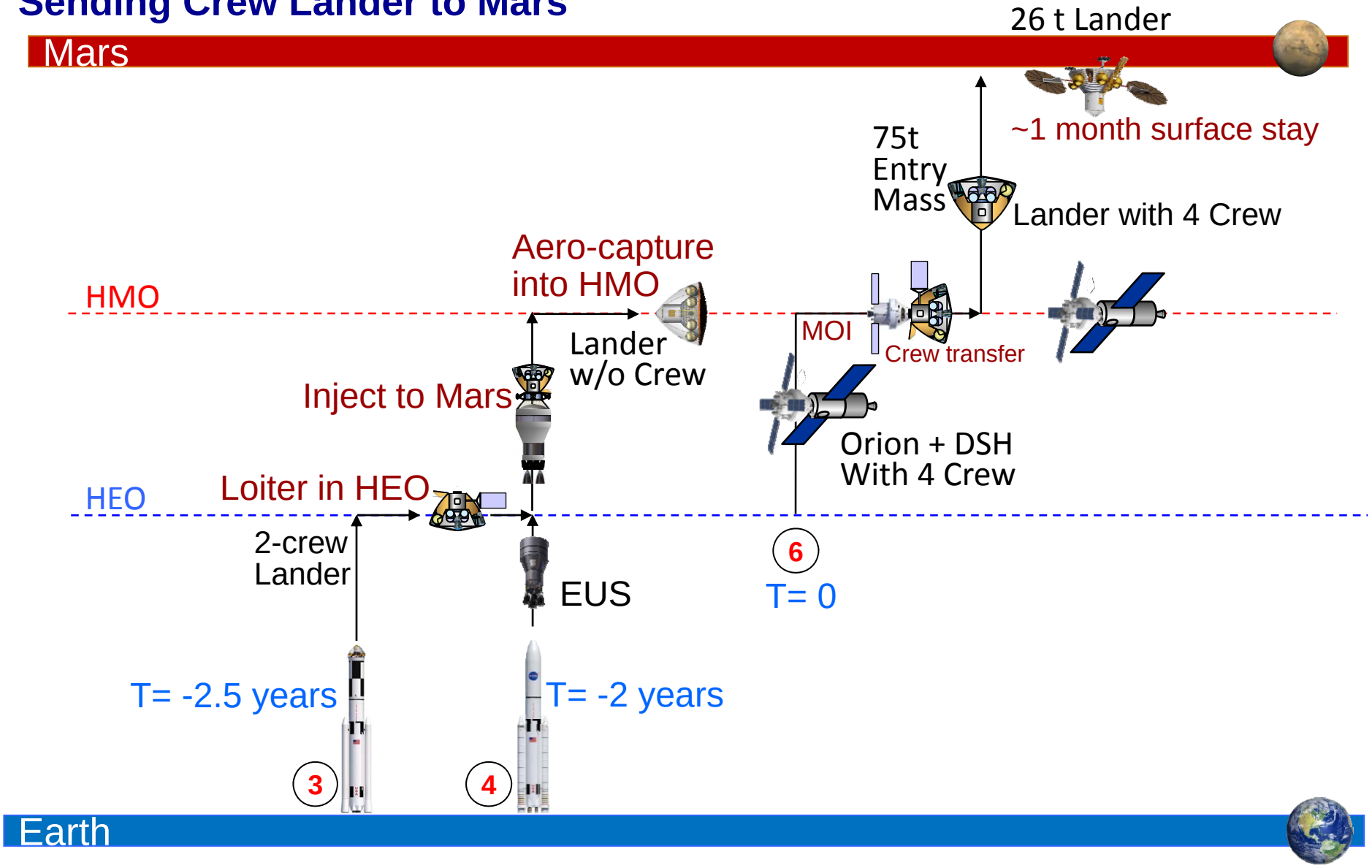
Third and Fourth Launches

Sending Crew Lander to Mars



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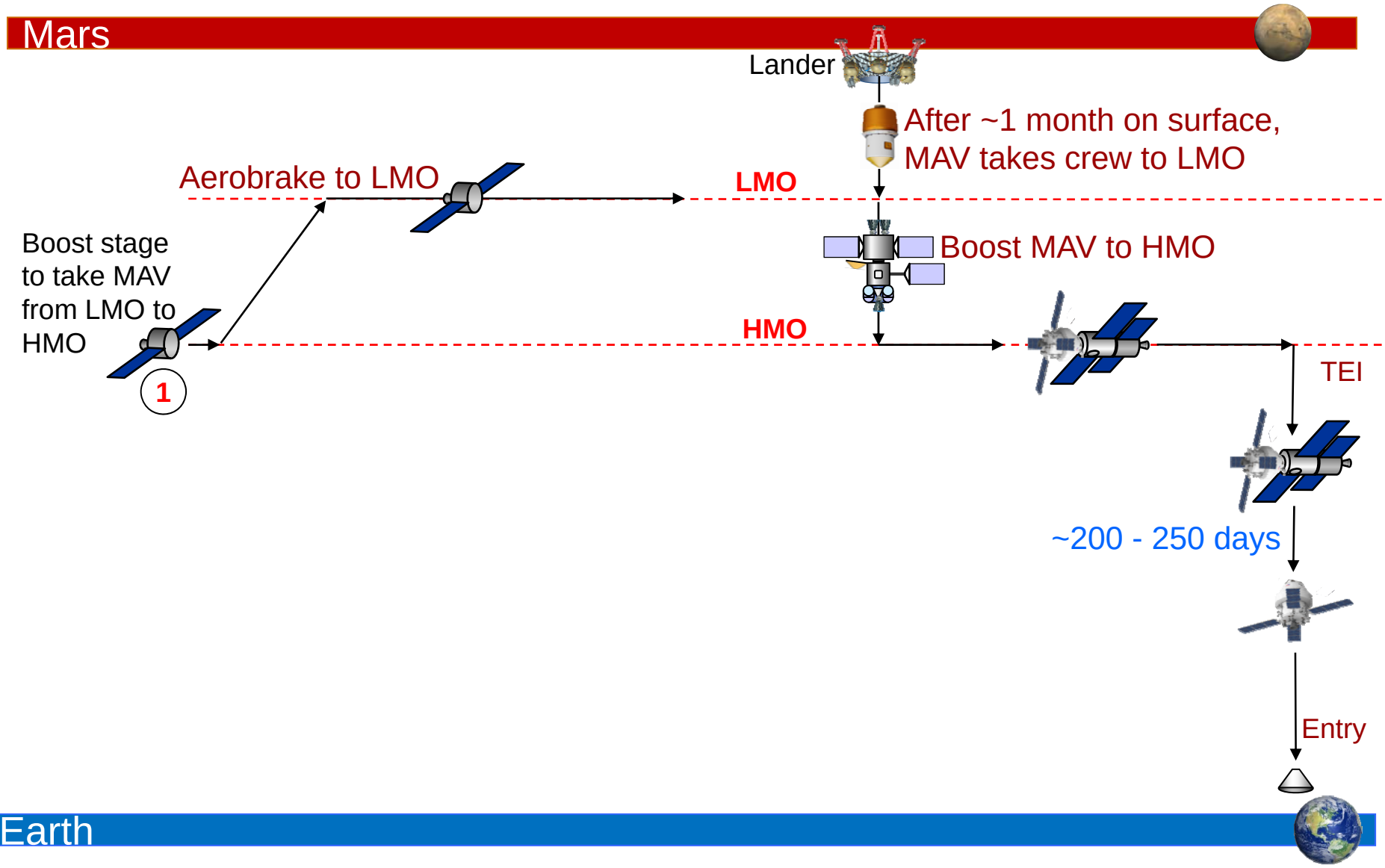
Return to Earth



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Descent/Ascent Vehicle (DAV)

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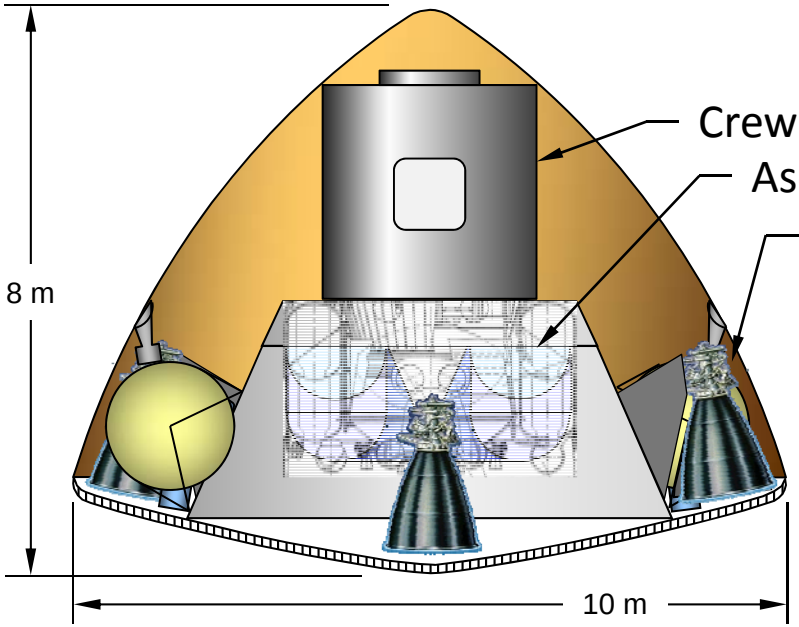
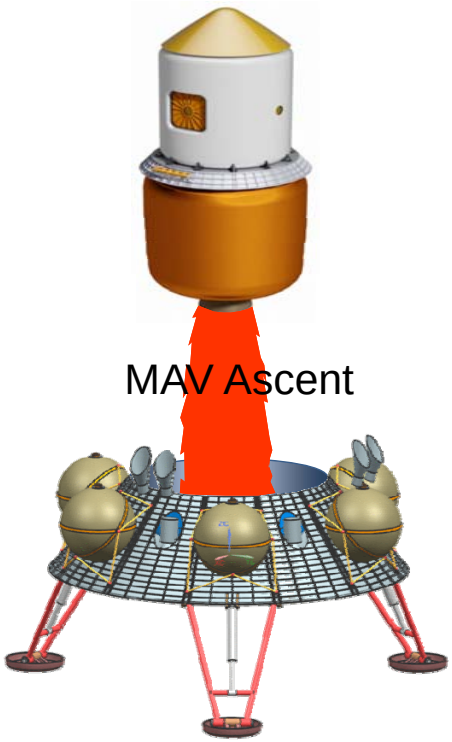
Can support crew of 2 for 28 days, or crew of 4 for 6 days

Launch



Landed Configuration



MAV Ascent

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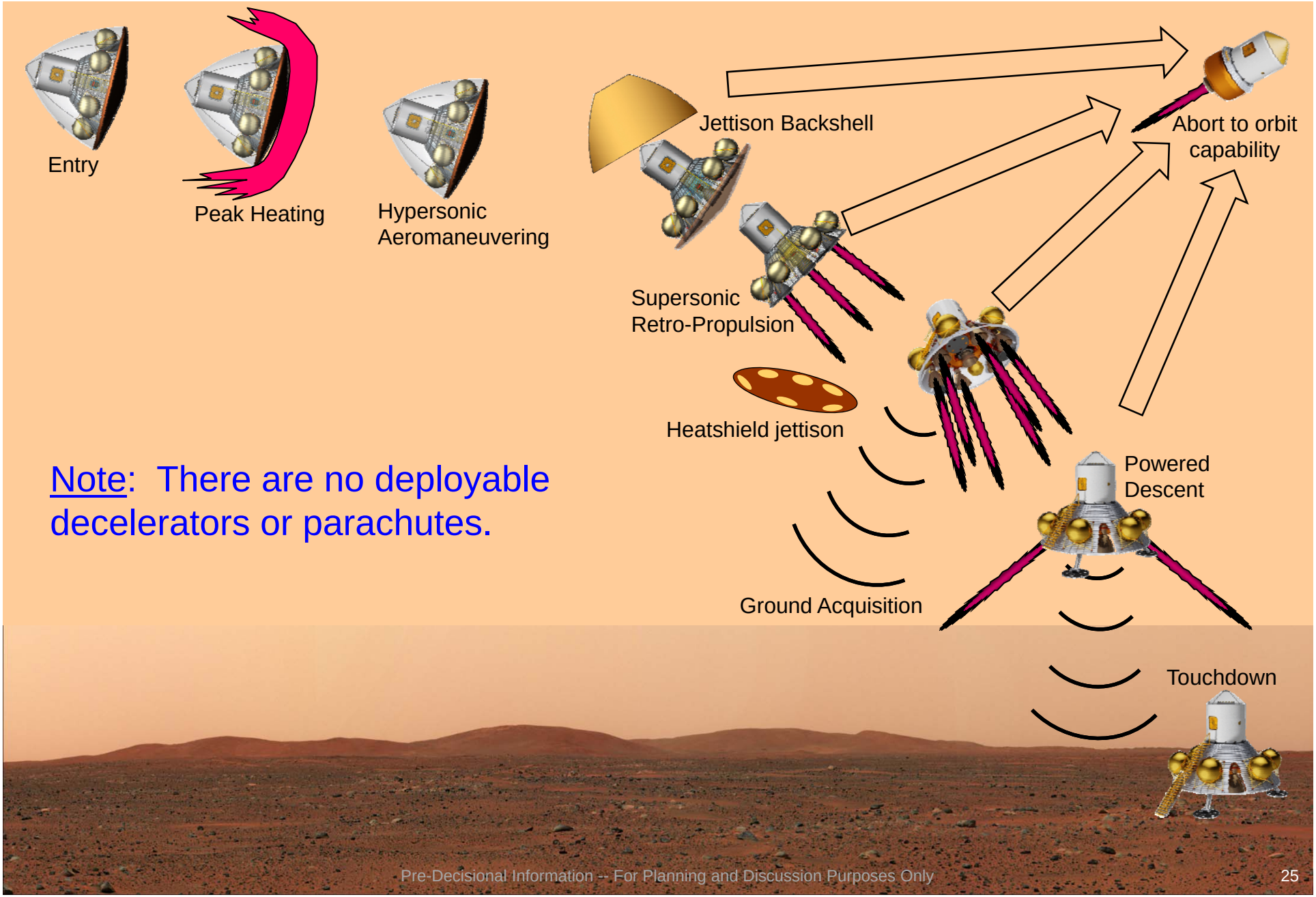
EDL Concept for Blunt Body Mars Lander



Note: There are no deployable decelerators or parachutes.

Six Vehicles to Enable Crewed Missions to Mars Surface (Short Stay)

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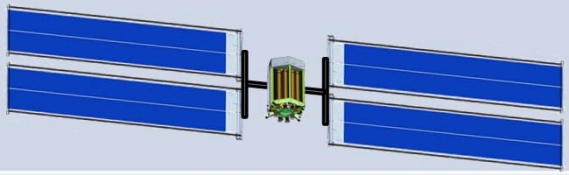
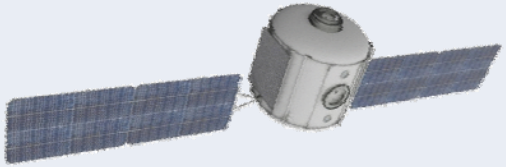
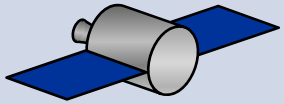
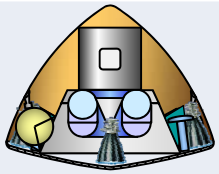
Vehicles	# Vehicles per Mission
Orion	1
SLS	6
SEP Tug ~100 kWe 	2
Deep Space Habitat (One is a resupply version) 	2
In-Space Chemical Propulsion Stage 	3
Mars Lander 	1

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One-Year Surface Mission

10 SLS Launches

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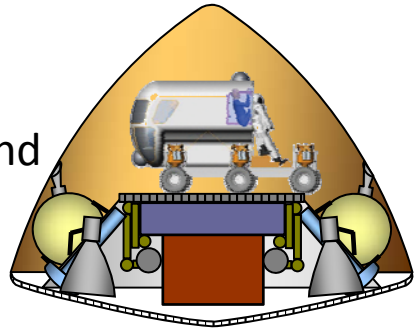
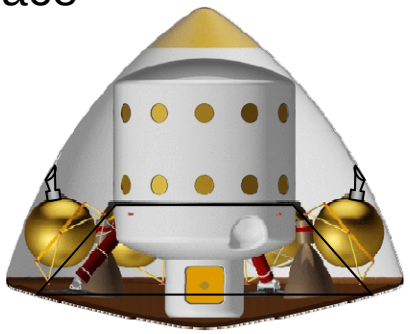
- Builds on the short-stay architecture but adds two additional landers
  - Four additional SLS launches (2 per cargo lander) are needed
  - 1st cargo lander carries a pressurized rover and other supplies
    - This arrives early enough to be used for the 1st surface mission
  - 2nd cargo lander carries the surface habitat
  - 3rd lander with MAV carries a crew of 4 to the surface

Cargo and logistics

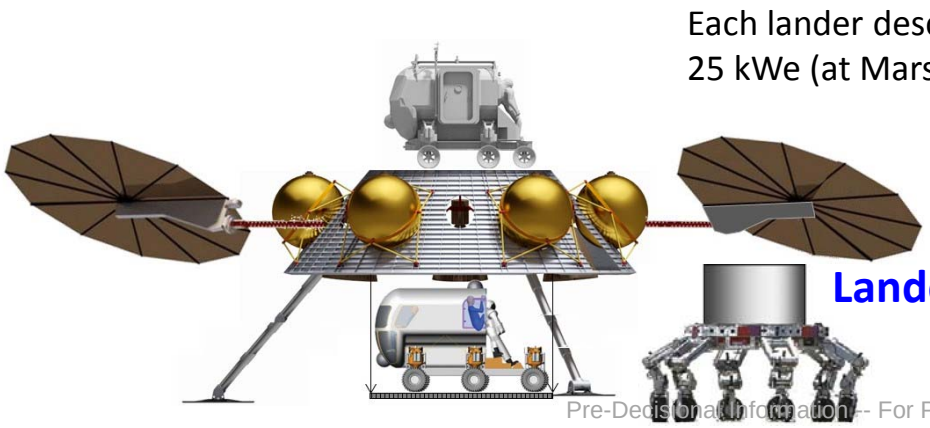


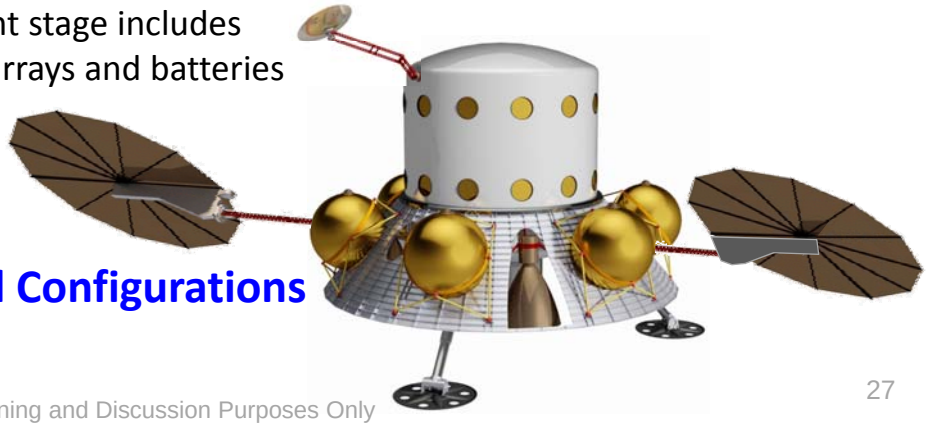
Entry Configurations



Surface habitat

Each lander descent stage includes
25 kWe (at Mars) arrays and batteries





Landed Configurations

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Long-Stay Surface Mission Concept

1 Year Surface Stay; Crew of 4; 10 SLS Launches

~400 t injected to Mars (155 t is propellant); 26 t MAV + 58 t useful cargo landed on Mars

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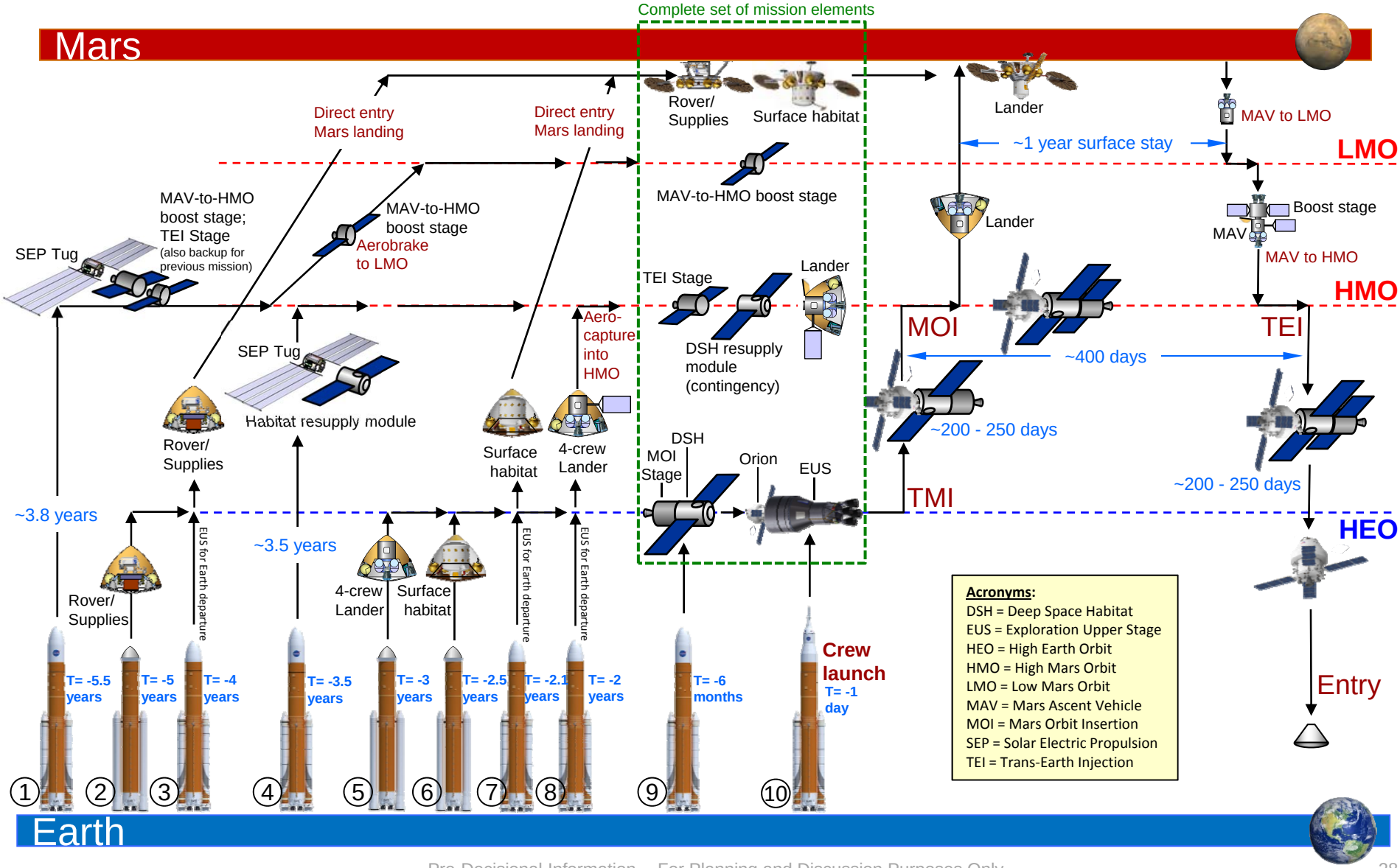
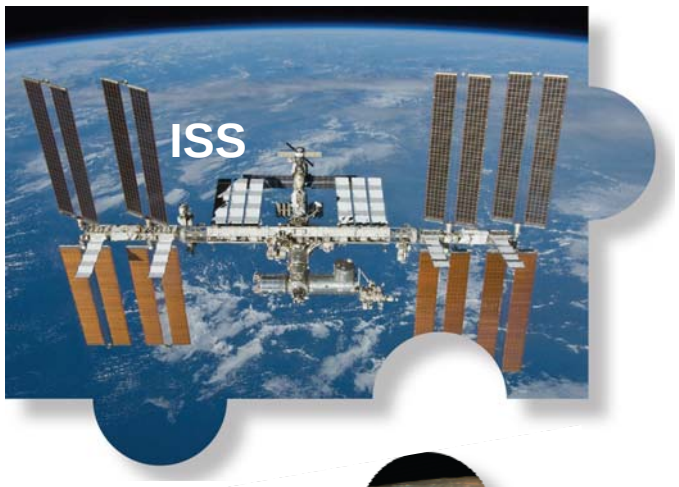
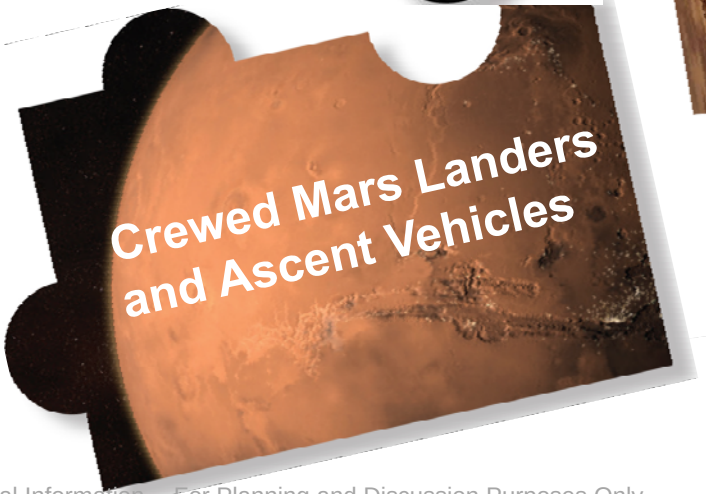


Acronyms:
DSH = Deep Space Habitat
EUS = Exploration Upper Stage
HEO = High Earth Orbit
HMO = High Mars Orbit
LMO = Low Mars Orbit
MAV = Mars Ascent Vehicle
MOI = Mars Orbit Insertion
SEP = Solar Electric Propulsion
TEI = Trans-Earth Injection

The Integrated Program

Fitting Together the Puzzle Pieces





Notional Timeline

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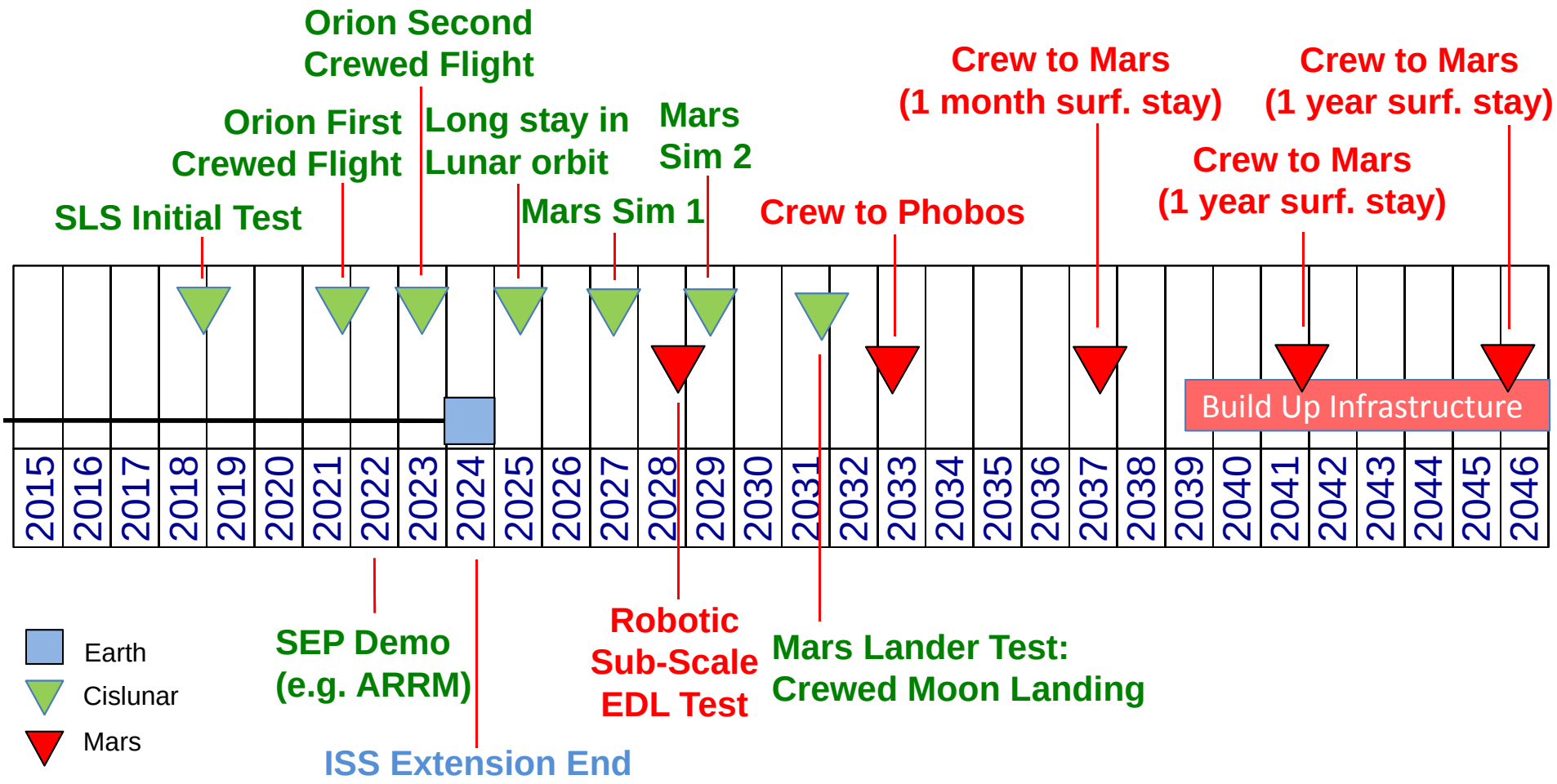

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Notional SLS Flight Scenario

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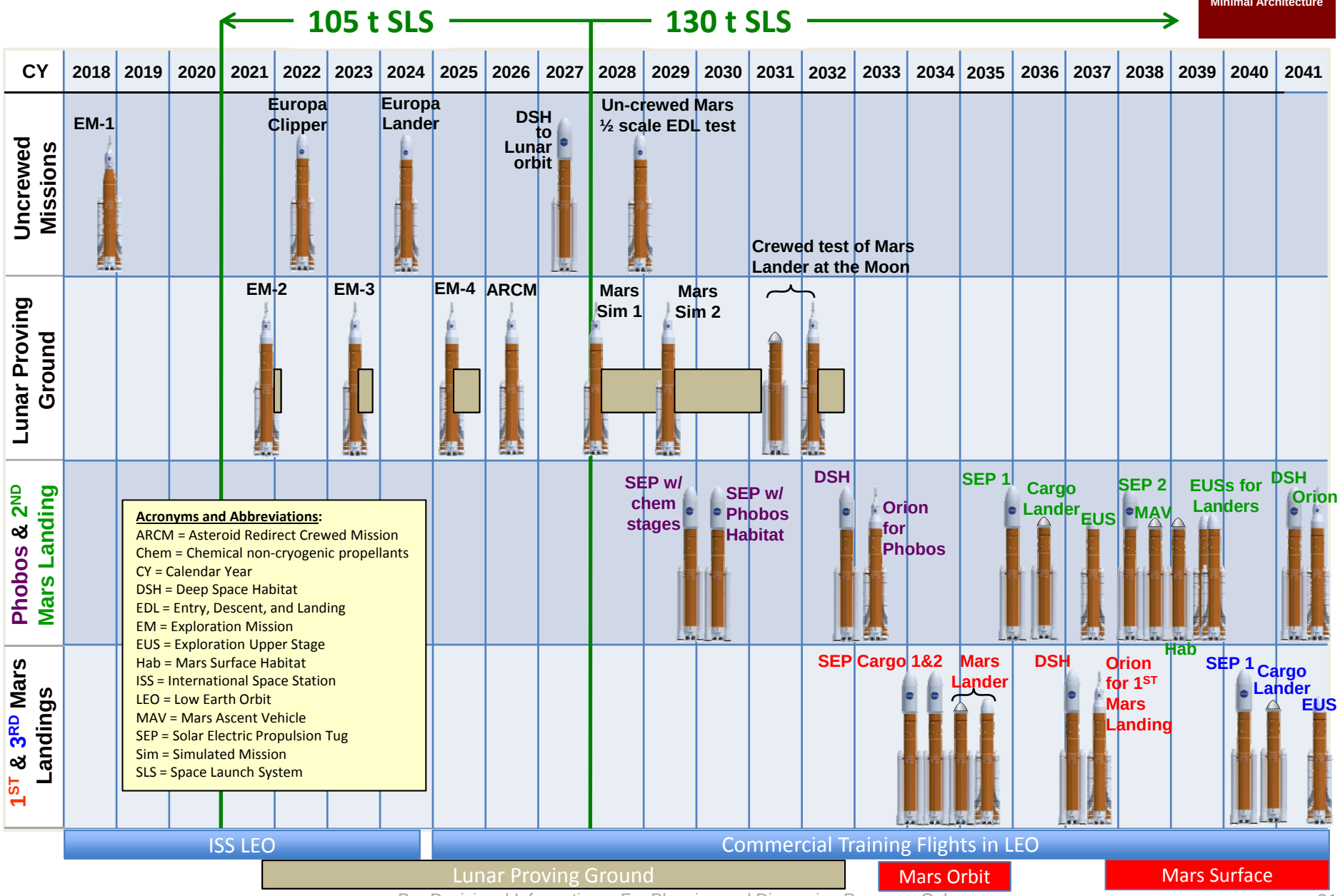

Cost “Sanity Check”

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- Aerospace Corporation performed the first-look cost assessment
- Cost estimates were based on models and analogy
  - Used model developed for NRC Pathways to Exploration study
  - As technical concepts mature, grassroots rather than model-based cost assessments should be performed for budget commitment
- We have recently updated the 2013 Aerospace cost assumptions to be consistent with the current 2016 budgets
- The flight gap after ISS was addressed by adding in 4 additional Lunar Proving Ground missions to what was in the original study
- Overall long-term affordability can still be achieved, possibly rescoping the 2033 mission, but there is a funding spike in the early 2020’s that results from developing new systems while still funding ISS

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Assumptions

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- Staging Orbit
  - Possible to stage in cislunar space to go to Mars but there is a performance penalty (months and delta-v of 100's m/s)
  - High Earth Orbit is the best staging orbit for performance
- No Re-use for Initial Missions
  - New systems for each mission allow for the design to evolve and improve over multiple versions (alla Apollo, etc.)
  - Unlikely to be an economic benefit until designs have significant flight history and in-space refurbishment technologies mature
- ISRU Not Used… at first
  - Storable prop results in use of current technology and more feasible MAV design with abort-to-orbit capability
  - Significantly reduces need for pre-placement of infrastructure before humans walk on Mars
  - Significantly reduces cost
  - ISRU utilization will be landing site dependent.
  - We have yet to fully understand the implications of ISRU

JPL Minimal Architecture

with ISS to 2024, first Mars landing in 2037

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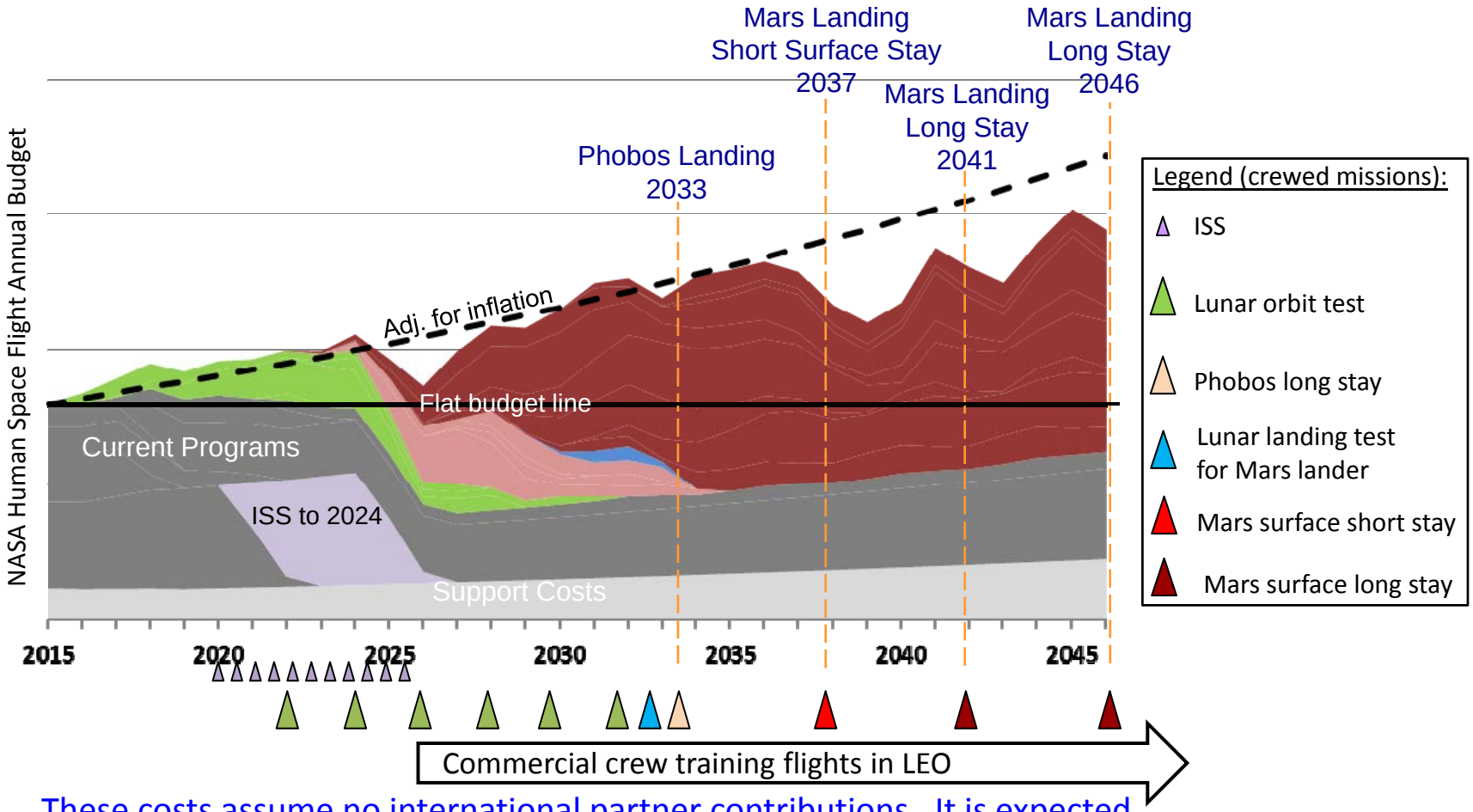
Original Aerospace Corp. estimate based on
2013 cost assumptions used for NRC "Pathways" study



These costs assume no international partner contributions. It is expected that international participation could reduce costs somewhat.

JPL Minimal Architecture

with ISS to 2024, first Mars landing in 2037

JPL revised estimate based on 2016 updates to cost assumptions used for NRC study

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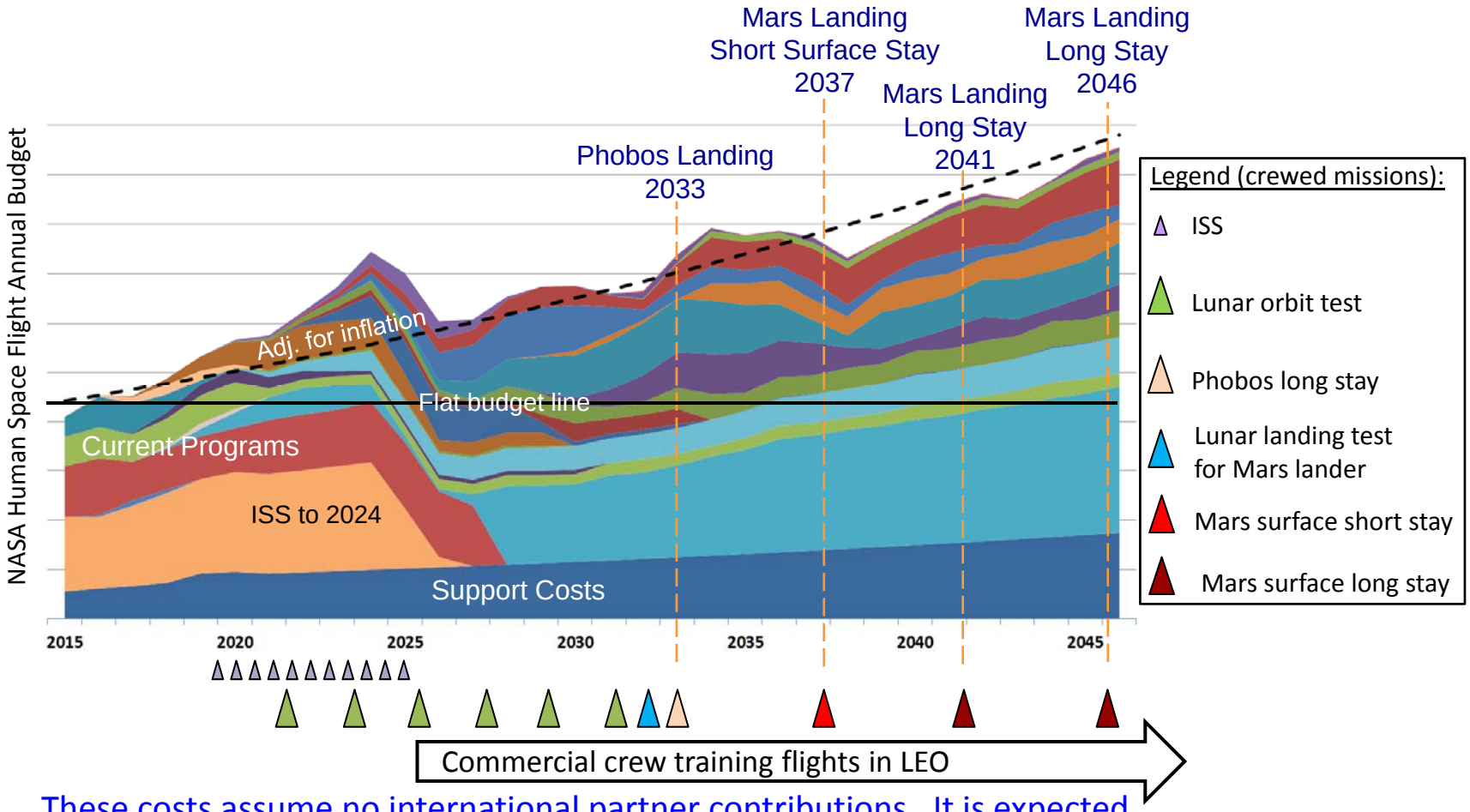

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Options for Reducing the Early 2020's Funding Peak

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1. Rescope the 2033 Mars orbit mission to be an opposition-class short-stay mission (~570 days)
   - ~30 days in Mars orbit
   - Phobos (and Deimos) would not be visited
   - Requires a second Trans-Earth Injection stage
     - In lieu of the Phobos transfer stage
   - Includes a Venus flyby on the return trip, which requires a large deployable sunshade for thermal control
2. Delay the Phobos and Mars landing missions by 2 years

Option for 2033 Short-Stay Orbit-Only

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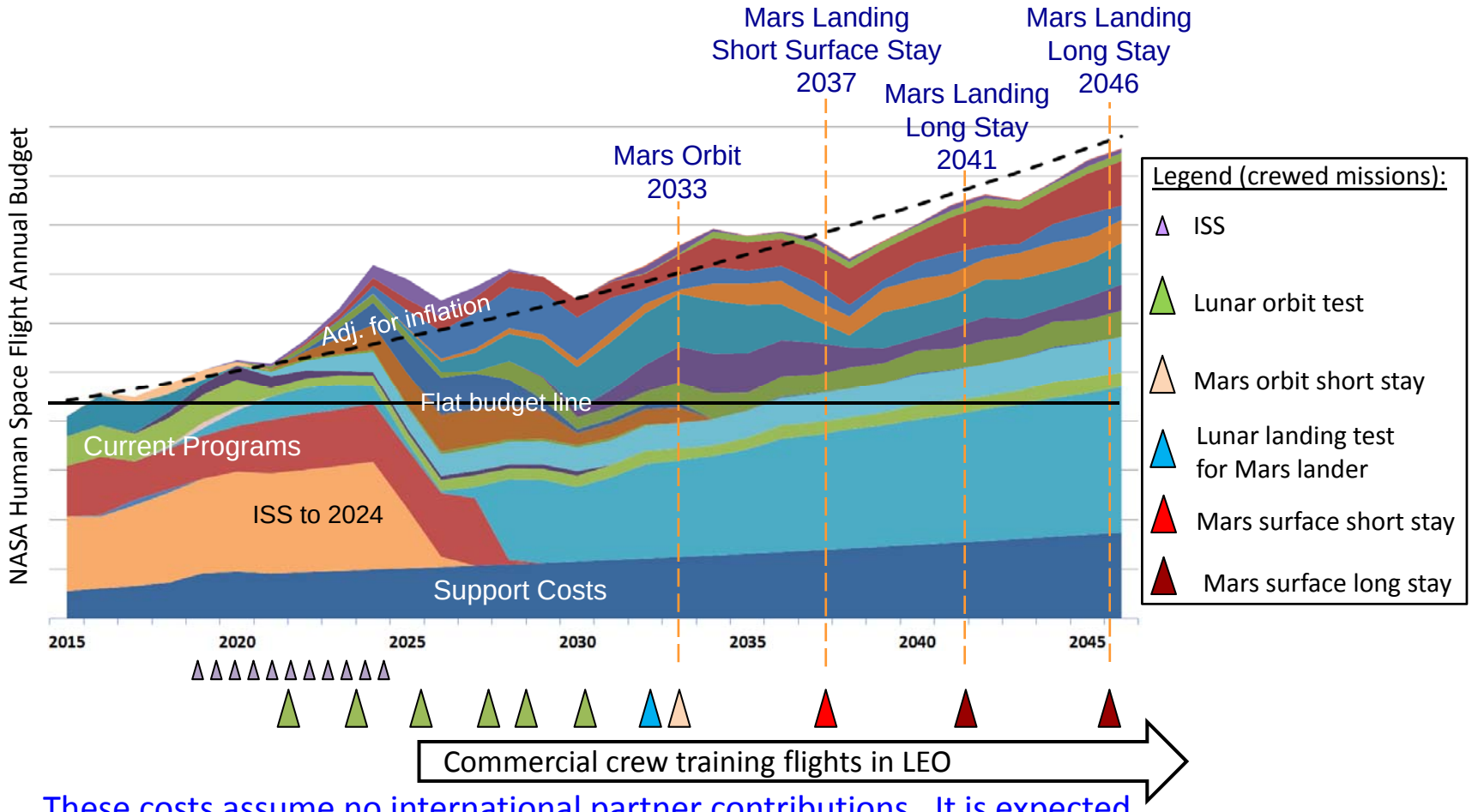
~570 day round trip, including Venus flyby gravity assist



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Option to Delay Phobos to 2035 and Mars Landing to 2039

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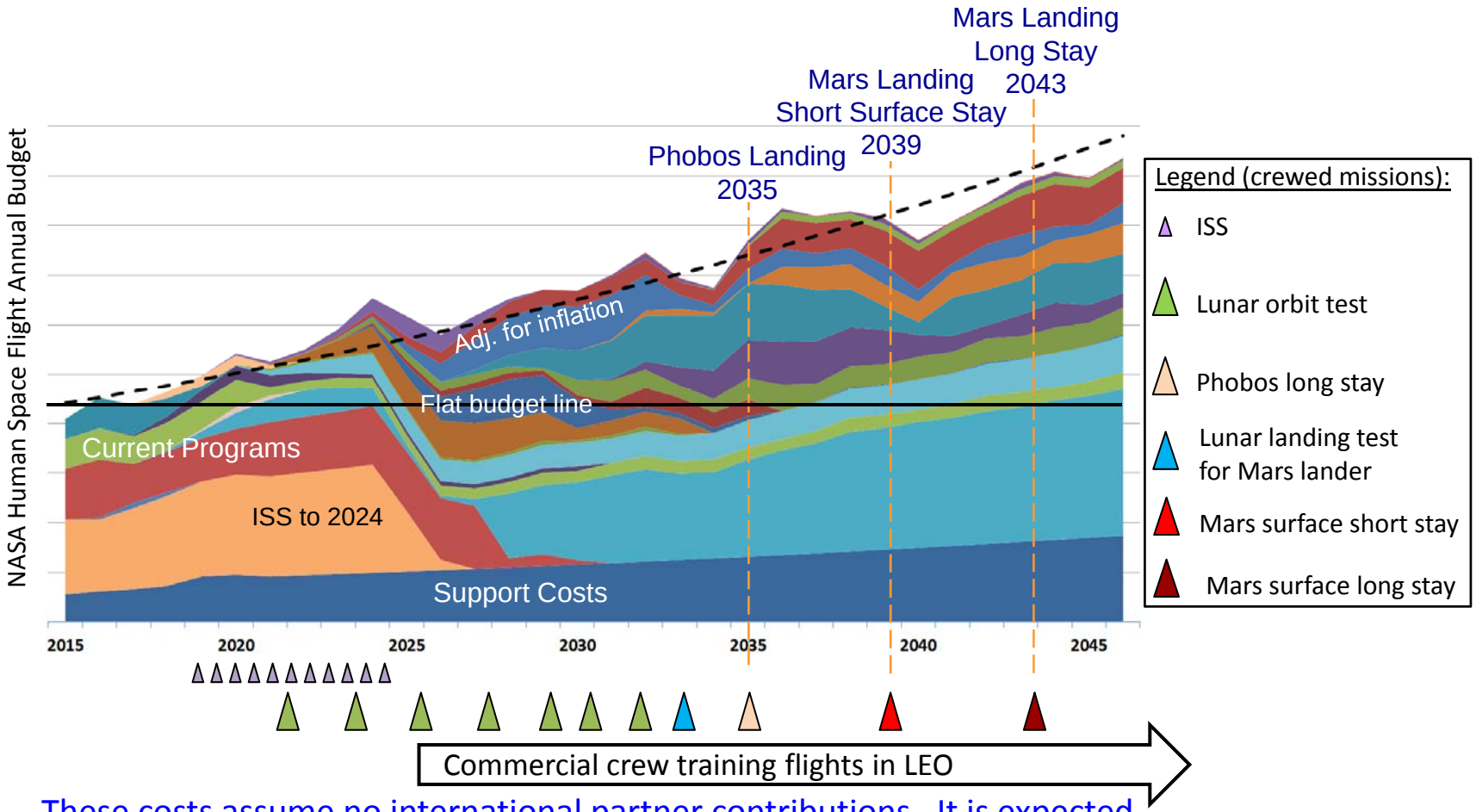

These costs assume no international partner contributions. It is expected that international participation could reduce costs somewhat.

This work was aimed at showing an example (an existence proof) that journeys to Mars using technologies that NASA is currently pursuing are plausible on a time horizon of interest to stakeholders and without large spikes in the NASA budget.

Takeaway

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Supplemental Material

Deep Space Habitat Concept

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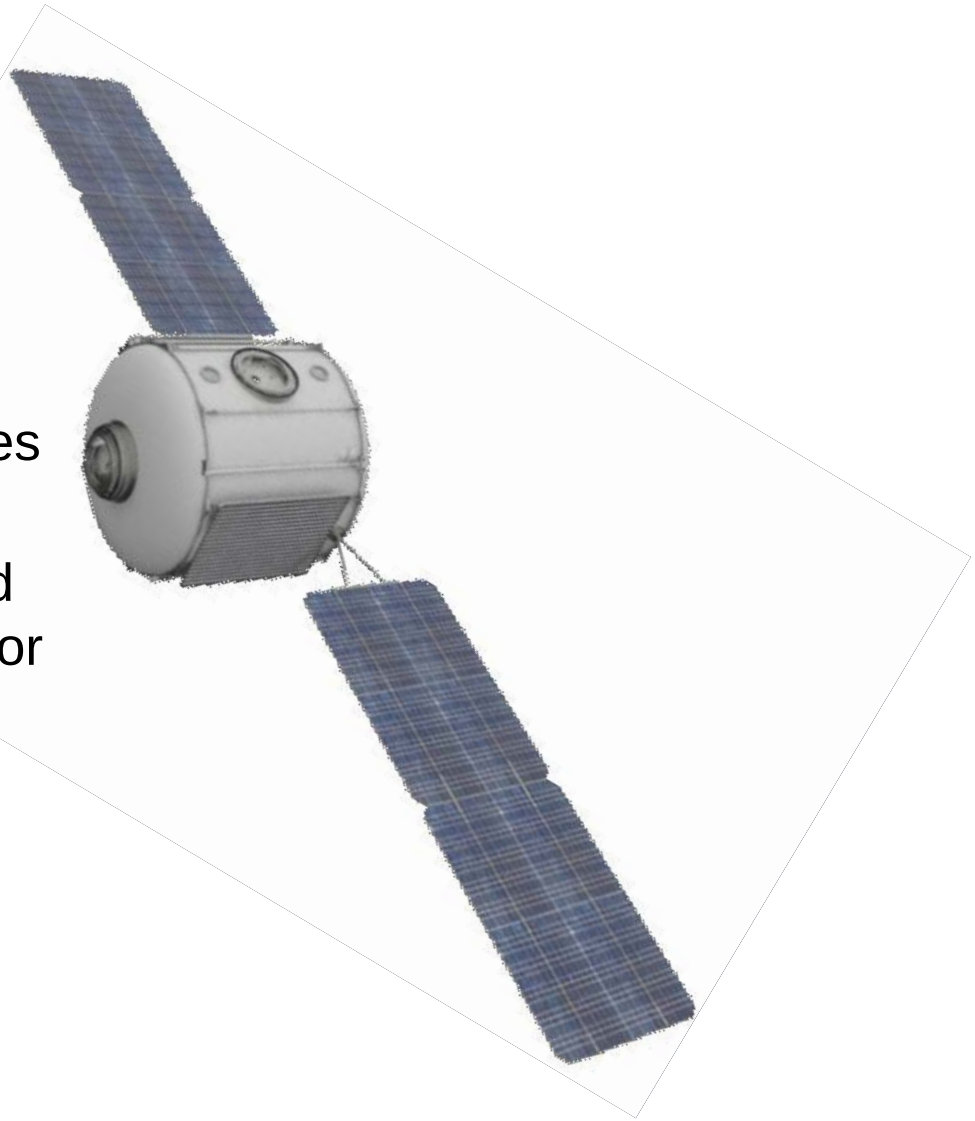
- Could support a crew of 4 for 500 days (transit to Mars and back)
- Mass is approximately 30 t.
- Requires solar arrays and batteries for power
- Attitude control would be provided by the attached propulsion stage or by Orion



Solar Electric Propulsion (SEP) Tug Concept

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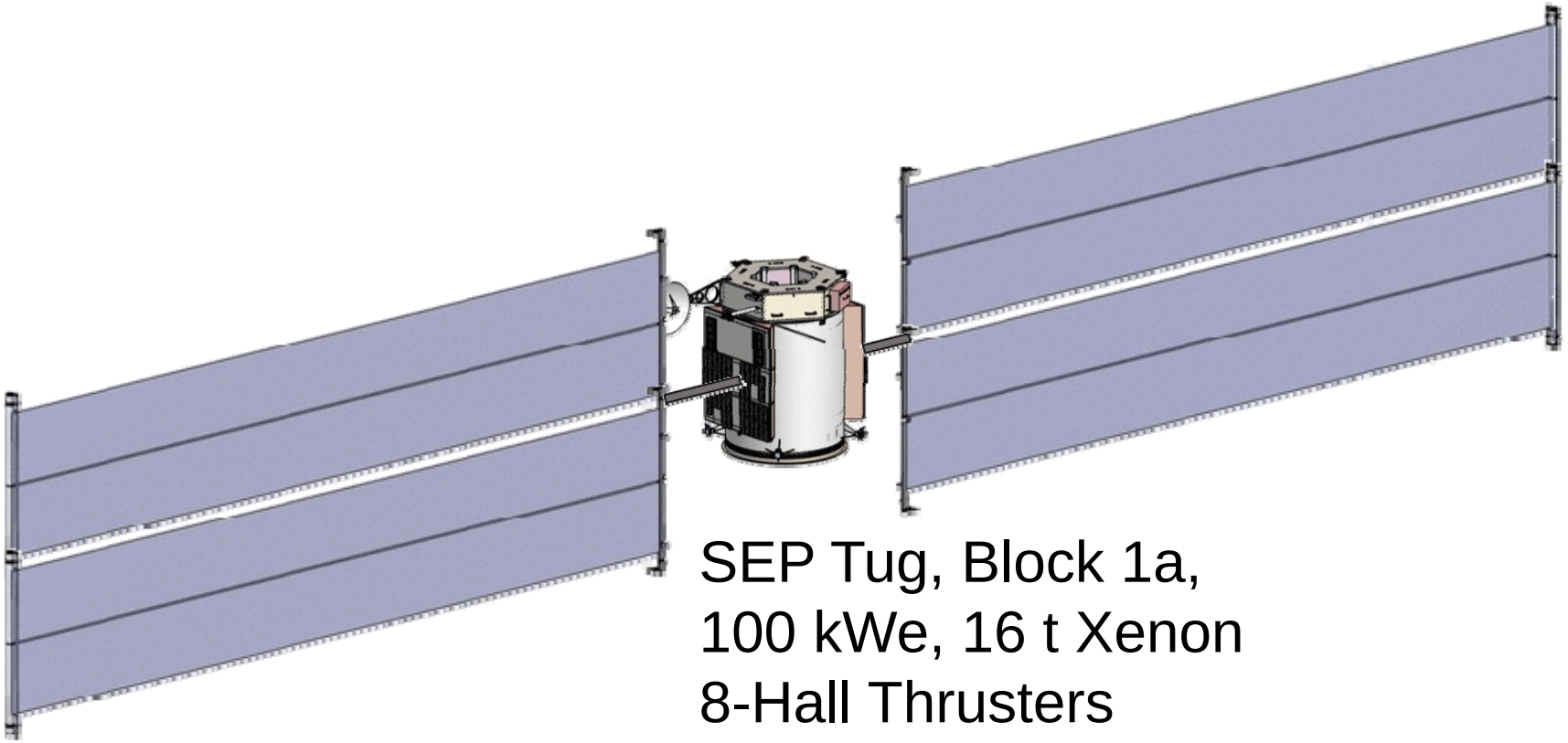
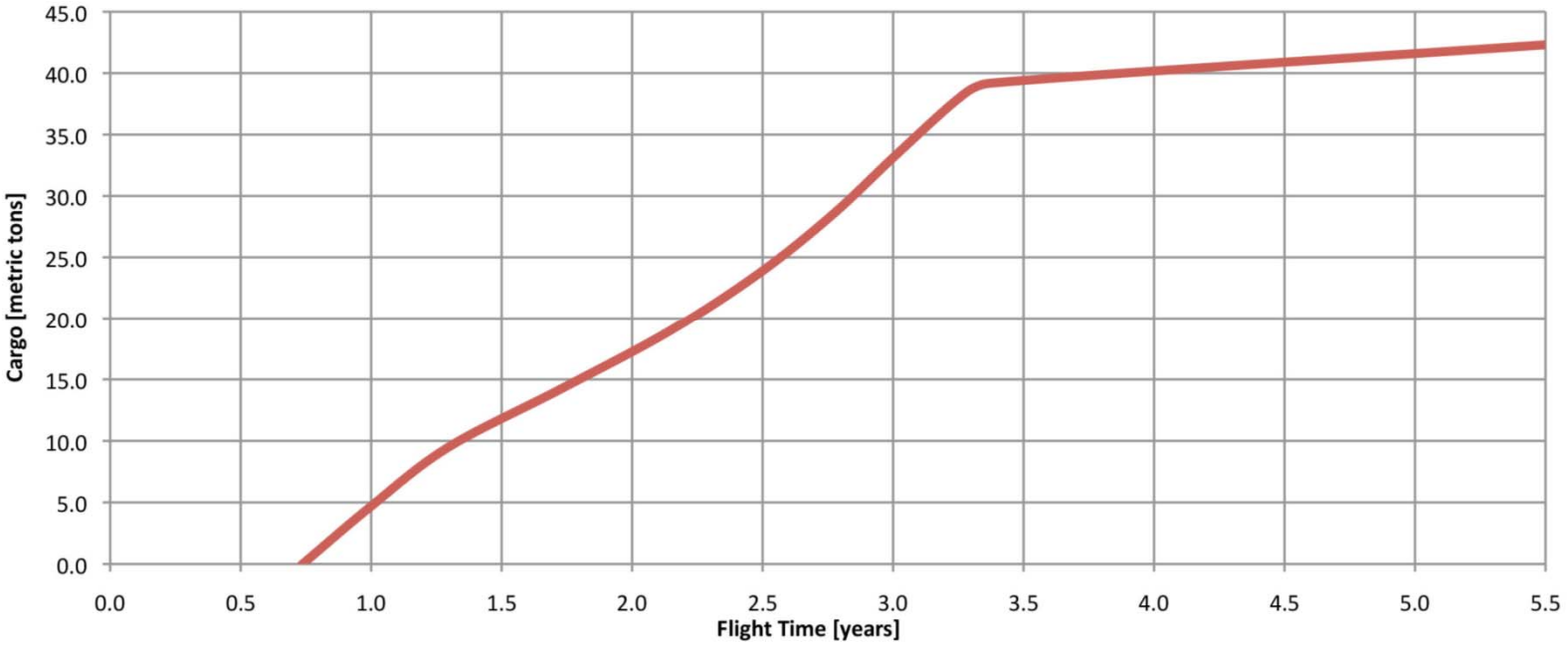


SEP Tug, Block 1a,
100 kWe, 16 t Xenon
8-Hall Thrusters

SLS Performance to High Mars Orbit with 100 kWe Class SEP

H2M
Minimal Architecture

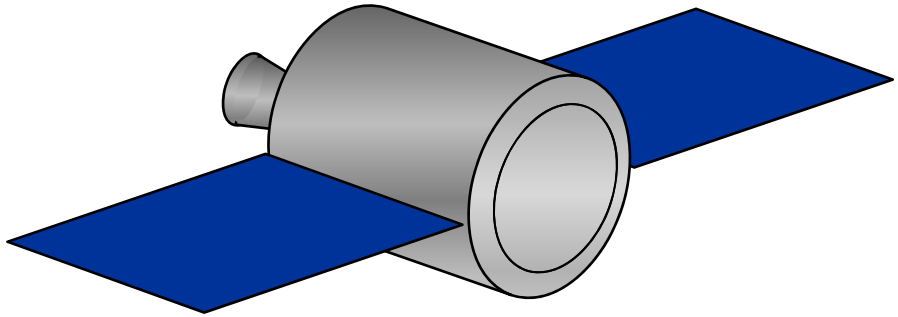
- With a single SLS launch, the 100 kWe SEP tug could deliver a 39 t payload to High Mars Orbit in about 3.3 years
- The knee in the curve corresponds to adding Earth spiral-out to the beginning of the mission
- There is a lot of flexibility in launch dates
  - Doesn't have to launch at traditional Mars opportunities



In-Space Chemical Propulsion Stage Concept

H2M
Minimal Architecture

- Would need 3 units, one each for
  - Mars Orbit Insertion (MOI),
  - MAV Boost Stage (MBS), and
  - Trans-Earth Injection (TEI)

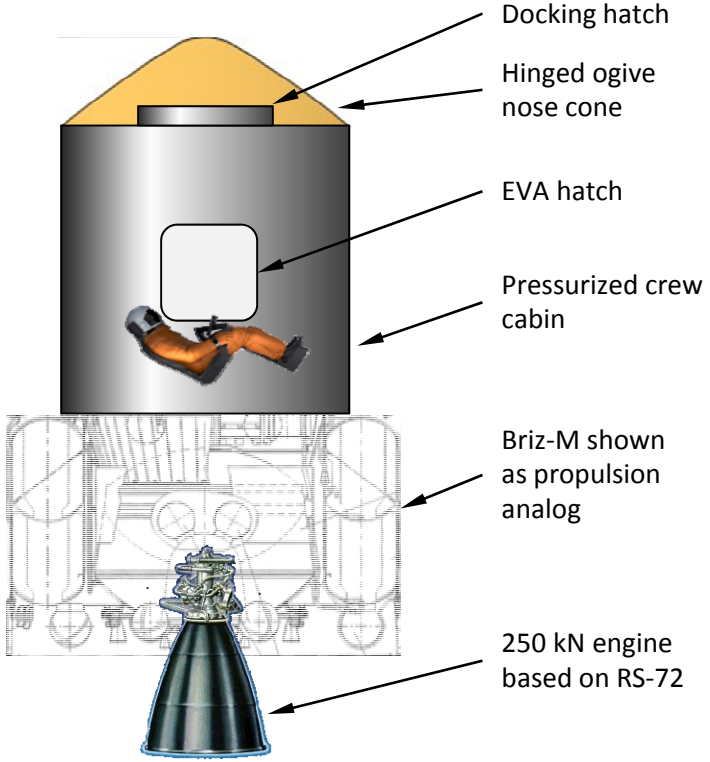


- MMH/MON-25 biprop stage with ~250 kN thrust pump-fed engine; similar in size to the Titan II second stage or Proton 3rd stage or Dnepr 2nd stage
  - Could use two RS-72 engines as an alternative

Features of Example MAV Design

H2M
Minimal Architecture

- 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
  - Briz-M does stage outer toroidal tanks, but that benefit was not used here
  - 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 would be to Low Mars Orbit (LMO)
  - Must dock with boost stage in LMO to return to High Mars Orbit (HMO)
- Moldline concept is aerodynamic
  - Hinged nosecone would protect 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 would be reclined and on one level
- No airlock – Apollo LEM style



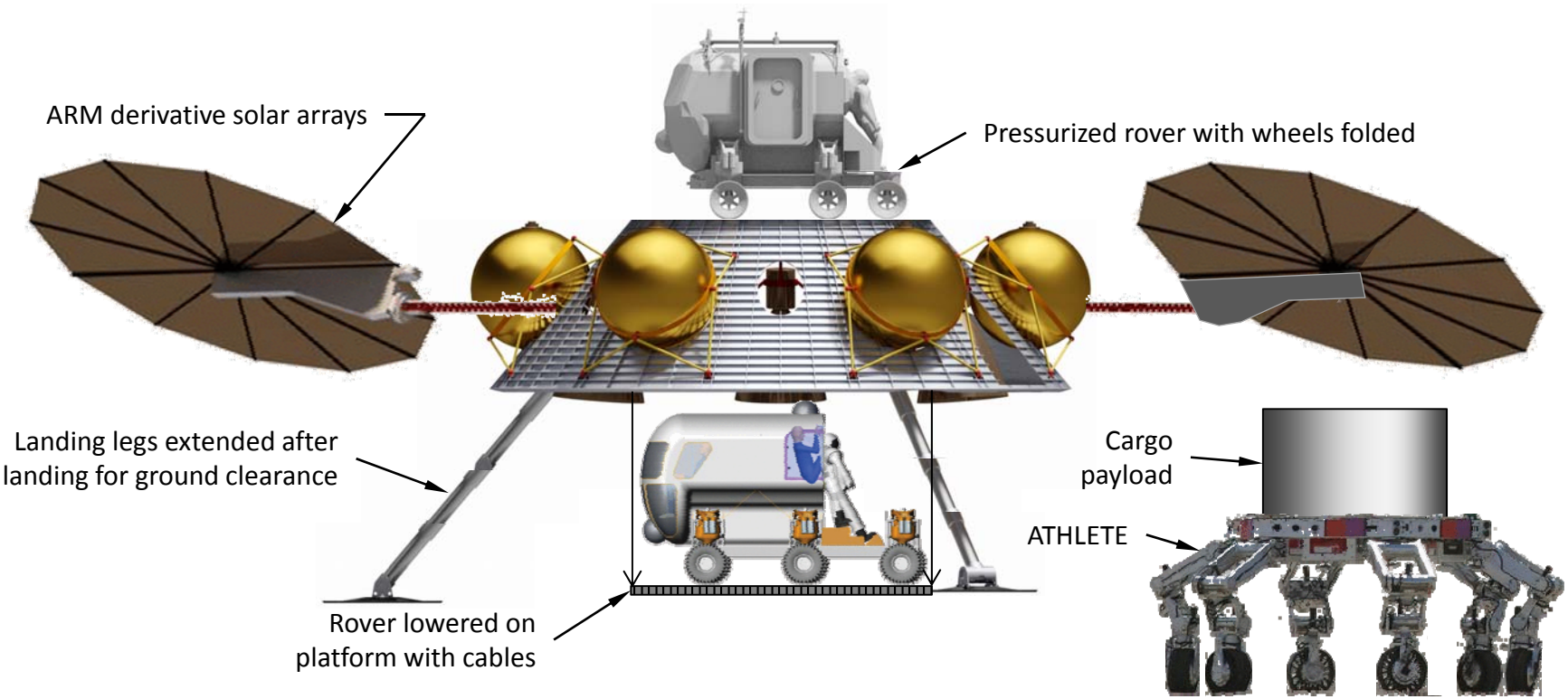
Assumptions for Mars Lander Descent Stage Propulsion

H2M
Minimal Architecture

- Pump-fed MMH/MON-25 bipropellant system for EDL
  - 6 engines at 250 kN thrust/engine
  - 6 spherical Ti tanks
  - 12:1 Throttle capability
  - Engines gimballed ~60° off vertical for final descent
    - Reduce soil/surface erosion directly underneath the vehicle
    - Blow debris out and away rather than up
    - Vehicle would be clocked to blow debris in directions away from nearby assets
- Separate RCS biprop thruster system for TCMs, aerocapture periapsis raise, orbit adjustments, de-orbit burn, and EDL 3-axis control

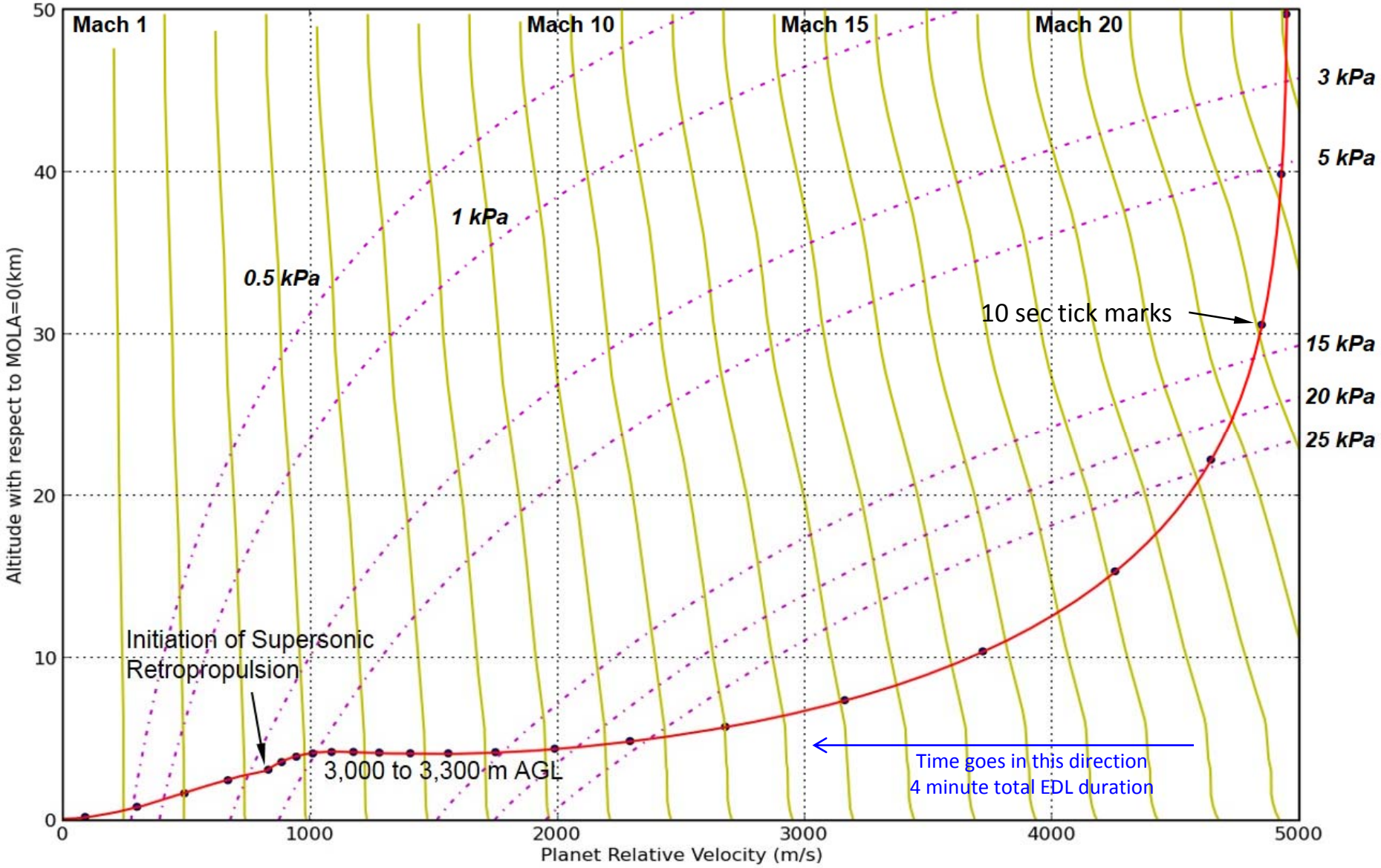
Mars Logistics Lander Concept

H2M
Minimal Architecture



EDL Trajectory for Blunt-Body Lander Concept

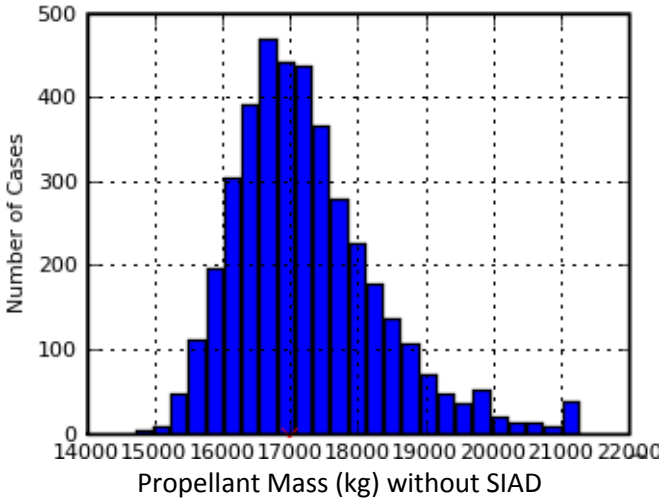
H2M
Minimal Architecture

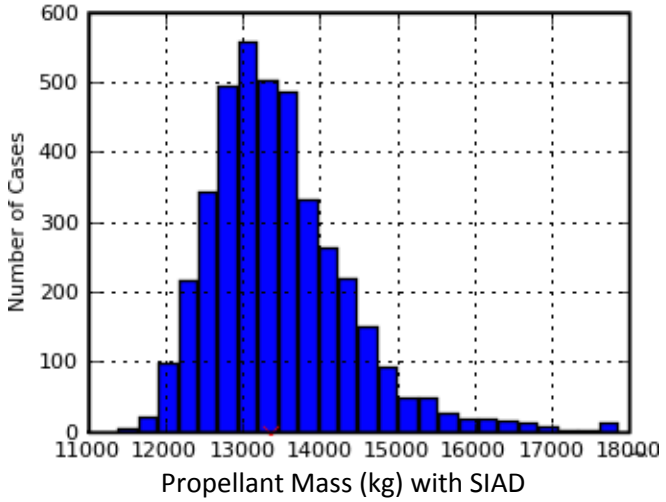


Selected EDL Monte Carlo Results

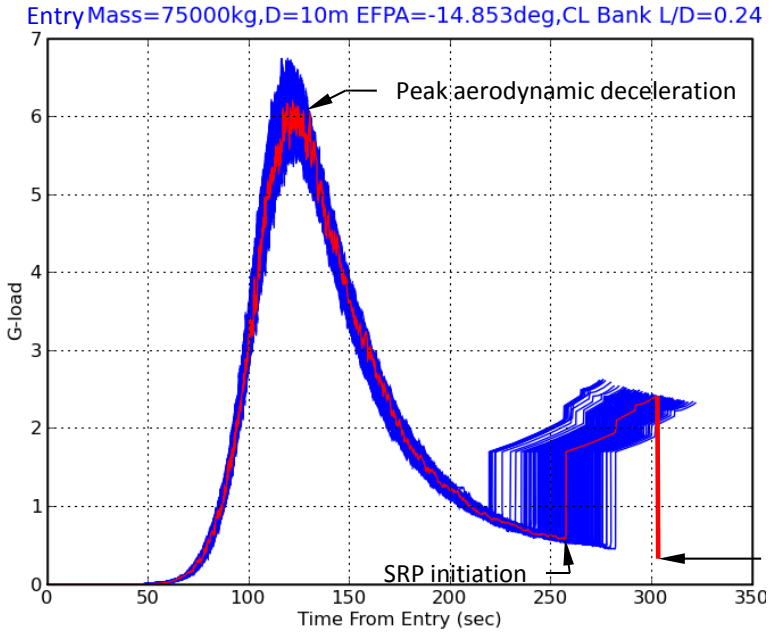
H2M
Minimal Architecture

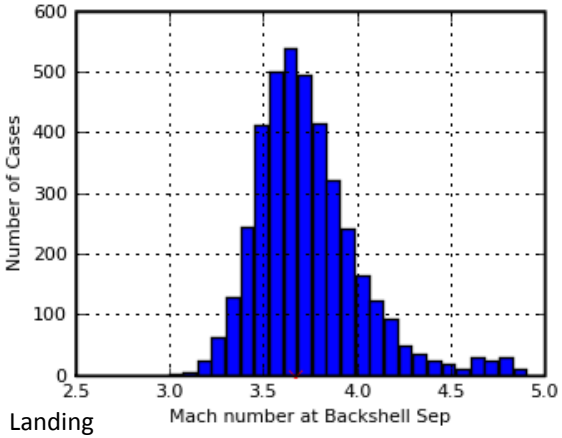
- ~20 t of propellant is used
- Crew experiences ~6.5 g
- Backshell separation and SRP is at ~Mach 3.8 and 4 kPa

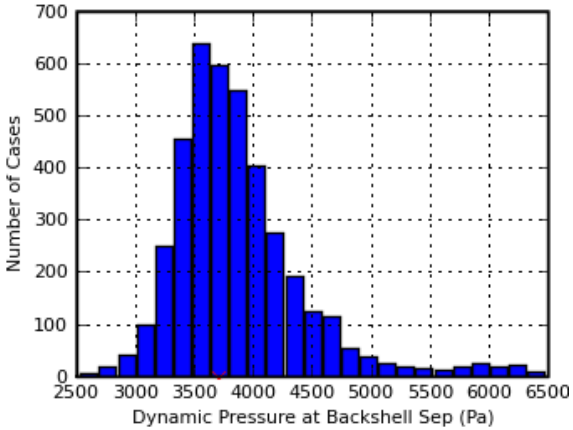




LDSD derived SIAD could save ~4 t of propellant







SLS Two-Launch Scenario

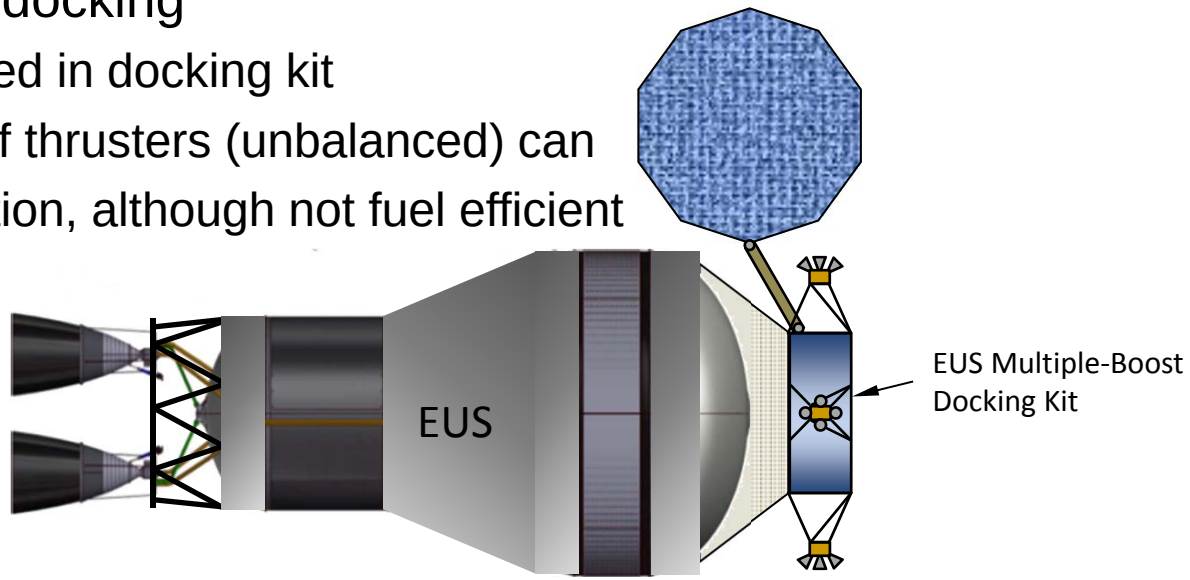
H2M
Minimal Architecture

- 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

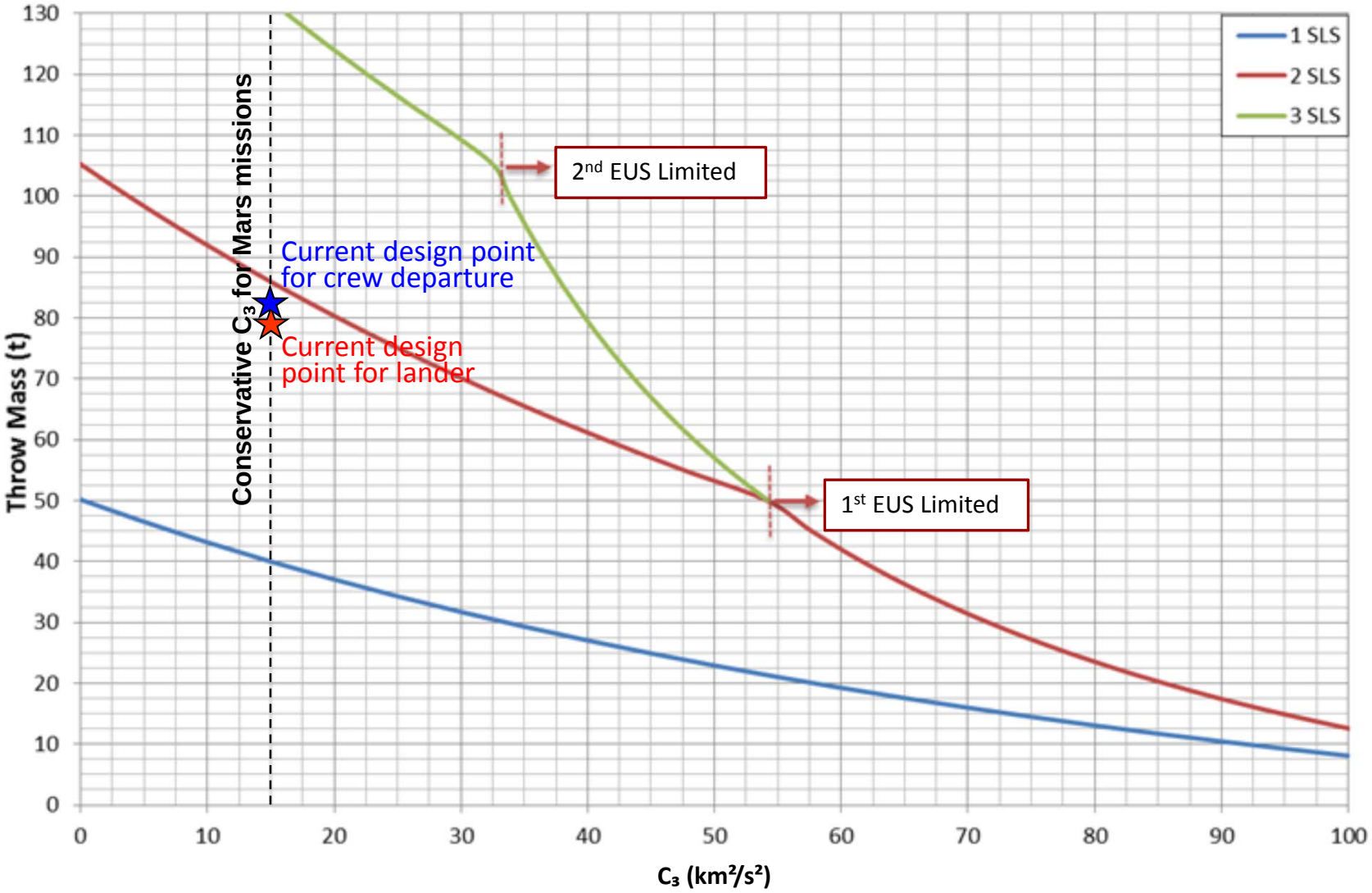
H2M
Minimal Architecture

- 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



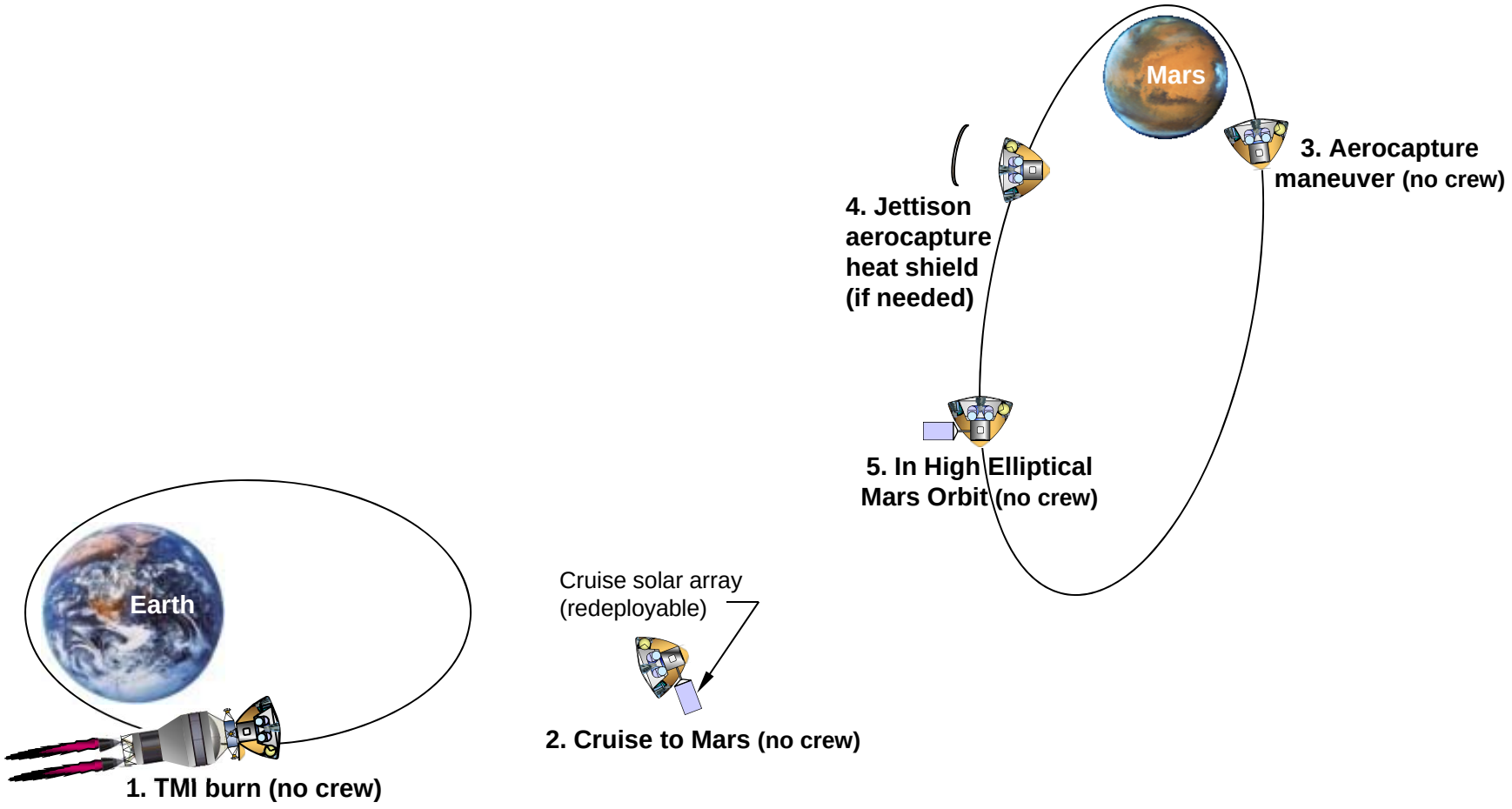
SLS Estimated Performance for Trans-Mars Injection (TMI) with single or multiple launches

H2M
Minimal Architecture



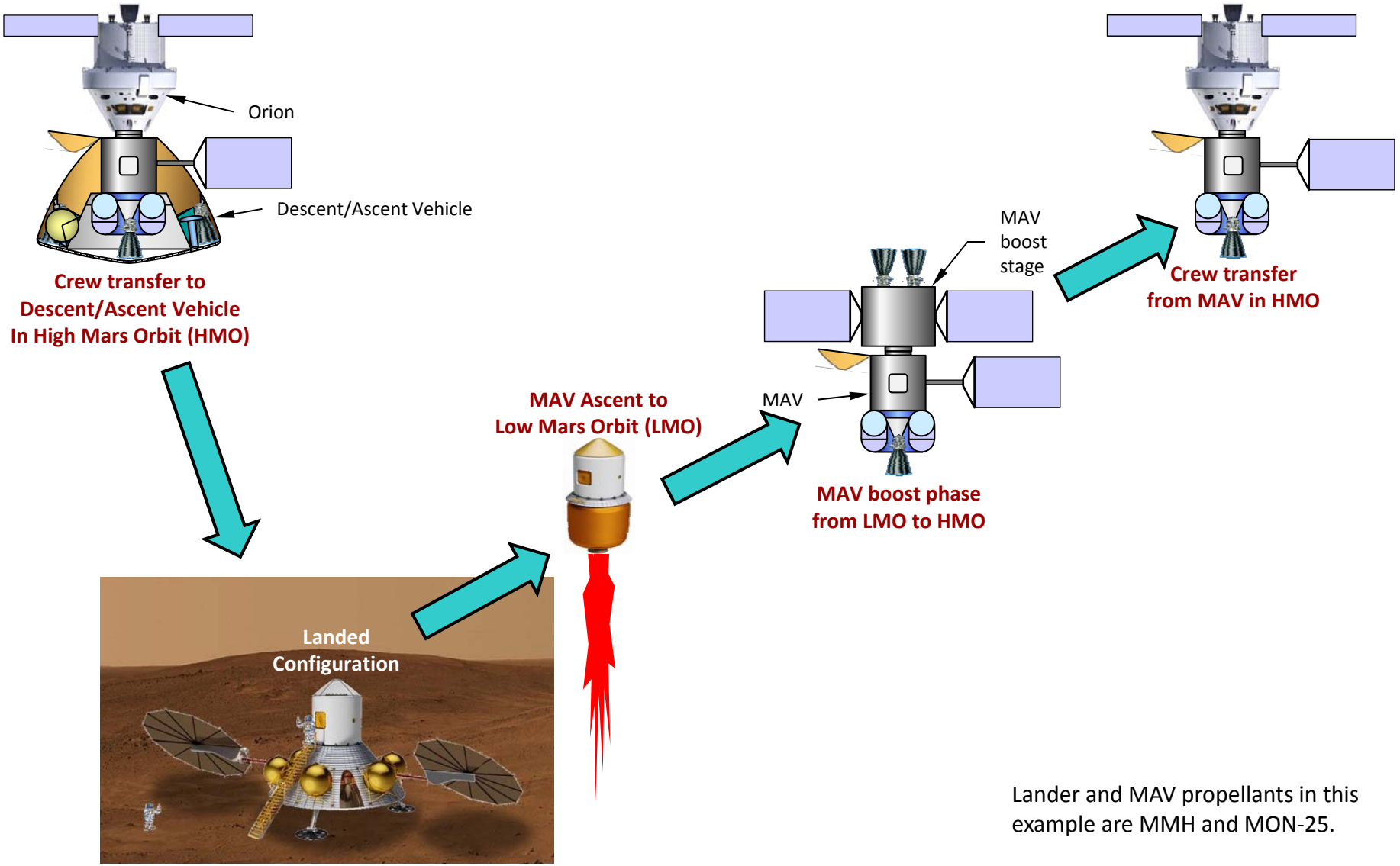
Concept for Descent/Ascent Vehicle (DAV)
Transit to High Mars Orbit

H2M
Minimal Architecture



Crewed Mars Descent/Ascent Vehicle Concept

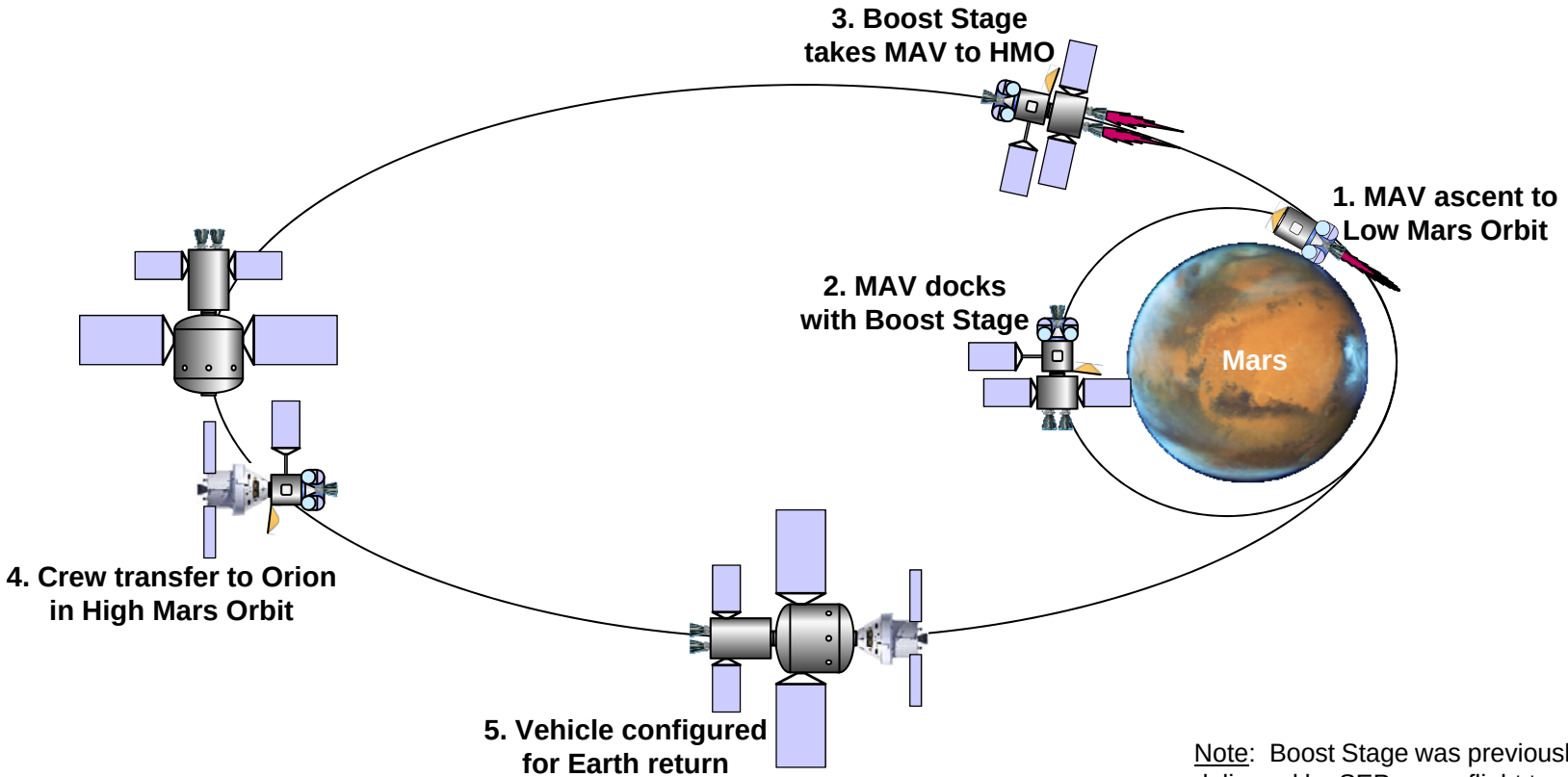
H2M
Minimal Architecture



Lander and MAV propellants in this example are MMH and MON-25.

Concept for MAV Ascent, Transfer to Deep Space Hab, and Preparation for Trans-Earth Injection

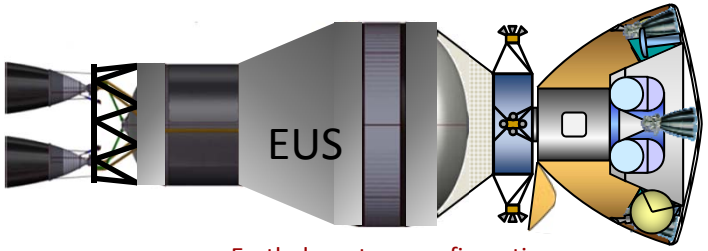
H2M
Minimal Architecture



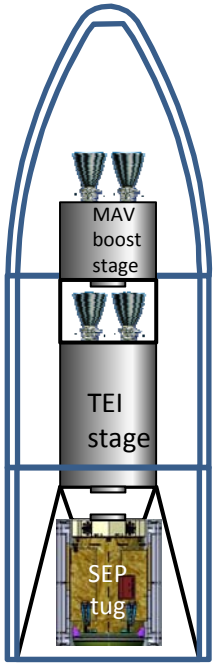
Note: Boost Stage was previously delivered by SEP cargo flight to HMO and aerobraked down to LMO.

SLS Block 2 Launch Concepts for Minimal Architecture
all 8.4 m fairings except for lander

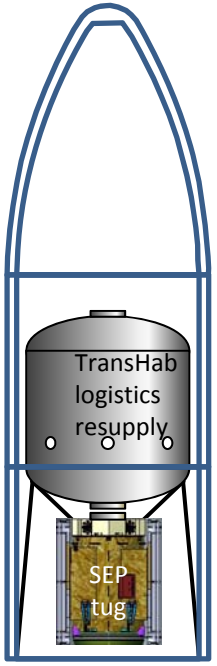
H2M
Minimal Architecture



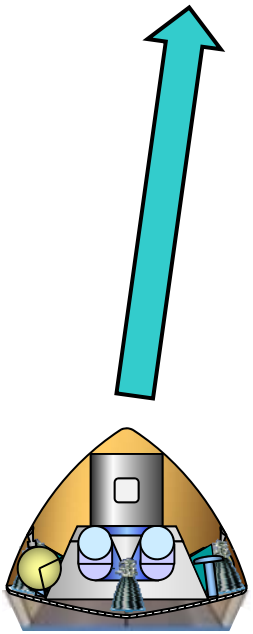
Earth departure configuration
for lander (from HEO)



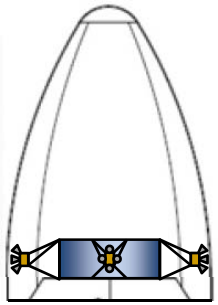
TEI and boost stage
cargo launch
Launch #1



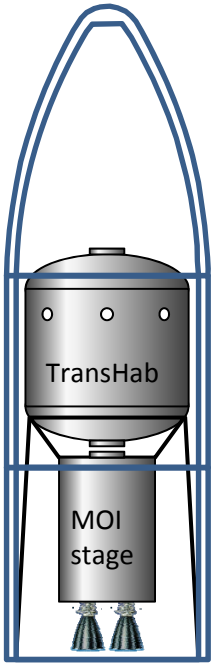
TransHab resupply
cargo launch
Launch #2



Lander to HEO using back-
shell as payload fairing
Launch #3



Docking kit for EUS to
use as departure stage
Launch #4



MOI stage and TransHab
launch to HEO
Launch #5

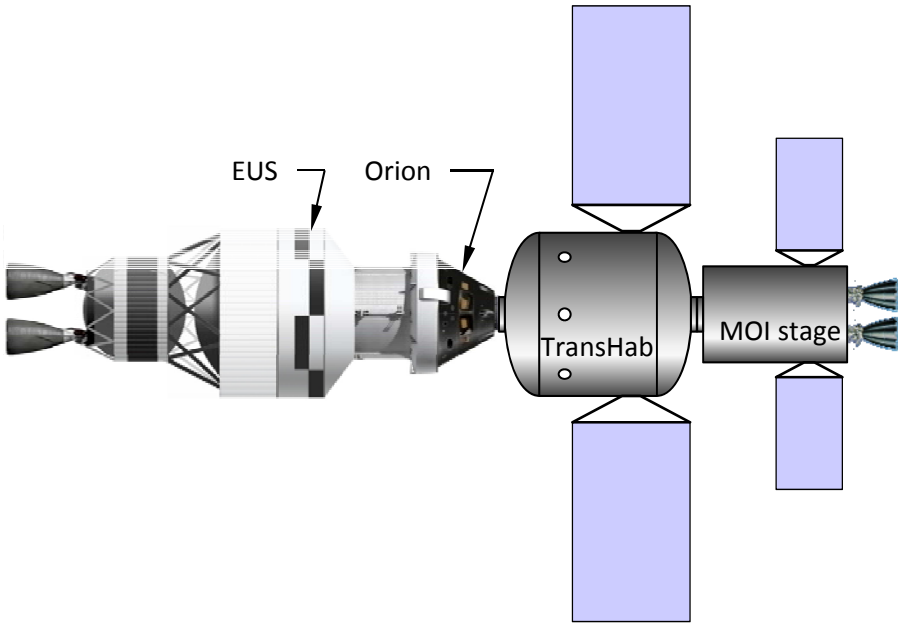
Orion with crew

Launch #6

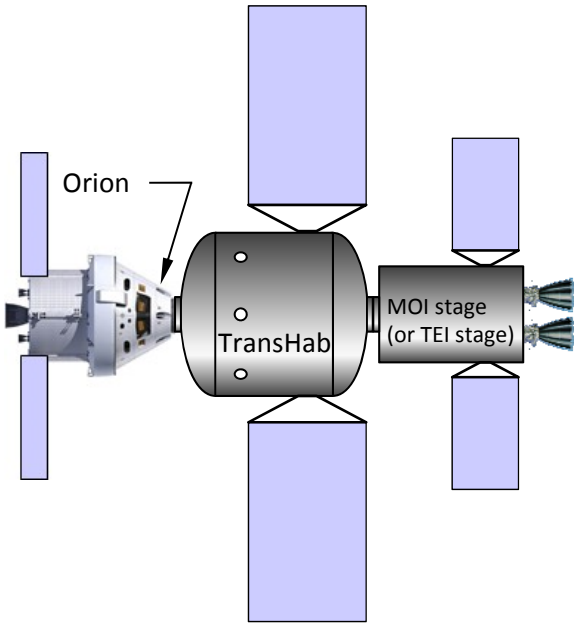
Launches #4 and #6 have limited launch periods. The other launches have flexible launch dates.

Notional Crewed Mars Transit Vehicle Configuration

H2M
Minimal Architecture



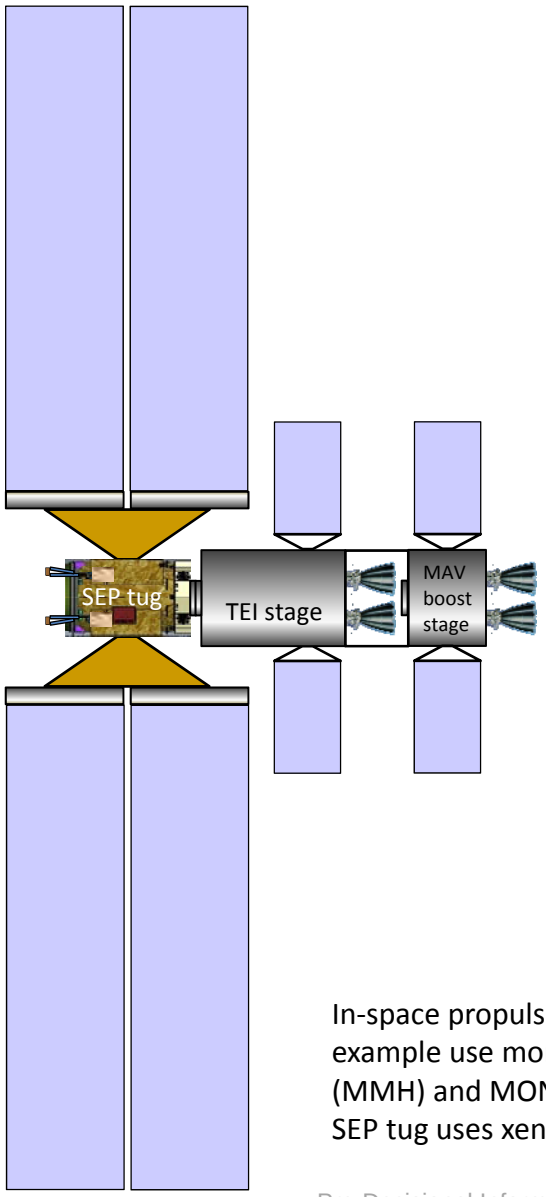
Earth departure configuration for crew

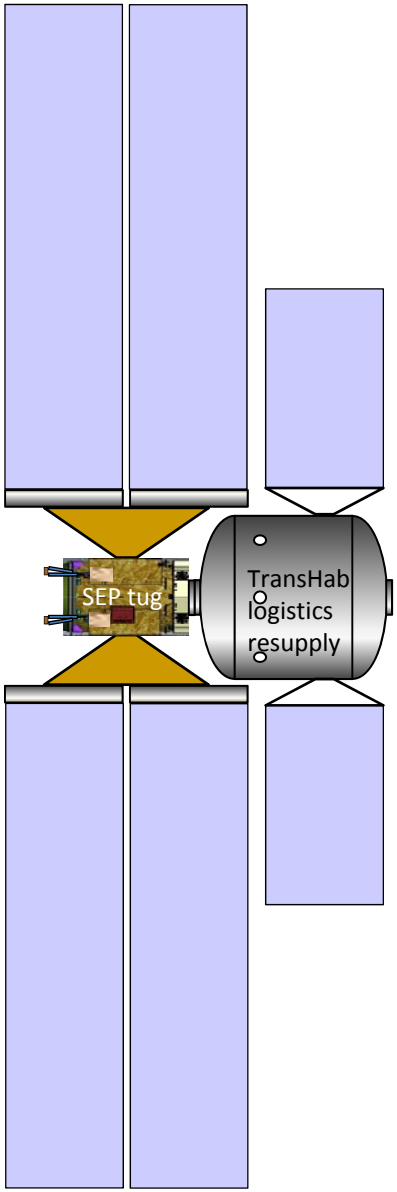


Earth/Mars transit configuration

Notional SEP Tug Cargo Flight Configurations

H2M
Minimal Architecture





In-space propulsion stages in this example use mono-methyl hydrazine (MMH) and MON-25 propellants.
SEP tug uses xenon propellant.

Background References

- Price, H., Baker, J., Naderi, F., “A Minimal Architecture for Human Journeys to Mars,” *New Space* Vol. 3, No. 2, June 2015.
- Price, H., Baker, J., Strange, N., Woolley, R., “Human Missions to Mars Orbit, Phobos, and Mars Surface Using 100-kWe-Class Solar Electric Propulsion,” AIAA Space 2014 Conference, San Diego, CA.
- Price, H., Manning, R., Sklyanskiy, E., Braun, R., “A High-Heritage Blunt-Body Entry, Descent, and Landing Concept for Human Mars Exploration,” AIAA SciTech 2016 Conference, San Diego, CA.
- The Humans to Mars Report 2016, Explore Mars, Inc.
- Human Exploration of Mars, Design Reference Architecture 5.0, NASA-SP-2009-566, July 2009.
- Human Exploration of Mars, Design Reference Architecture 5.0, Addendum, NASA-SP-2009-566-ADD.
- Human Exploration of Mars, Design Reference Architecture 5.0, Addendum 2, NASA-SP-2009-566-ADD2.
- Aldrin, B., Mission to Mars, National Geographic, 2013, ISBN 978-1426210174.
- Geels, S., “System Design of a Mars Ascent Vehicle,” M.S. Thesis, Dept. of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, 1990.
- Woodcock, G., “An Initial Concept of a Manned Mars Excursion Vehicle for a Tenuous Mars Atmosphere,” NASA Technical Memorandum X-53475, MSFC, June 7, 1966.