Human Mars Mission Operations from a Phobos Base Camp

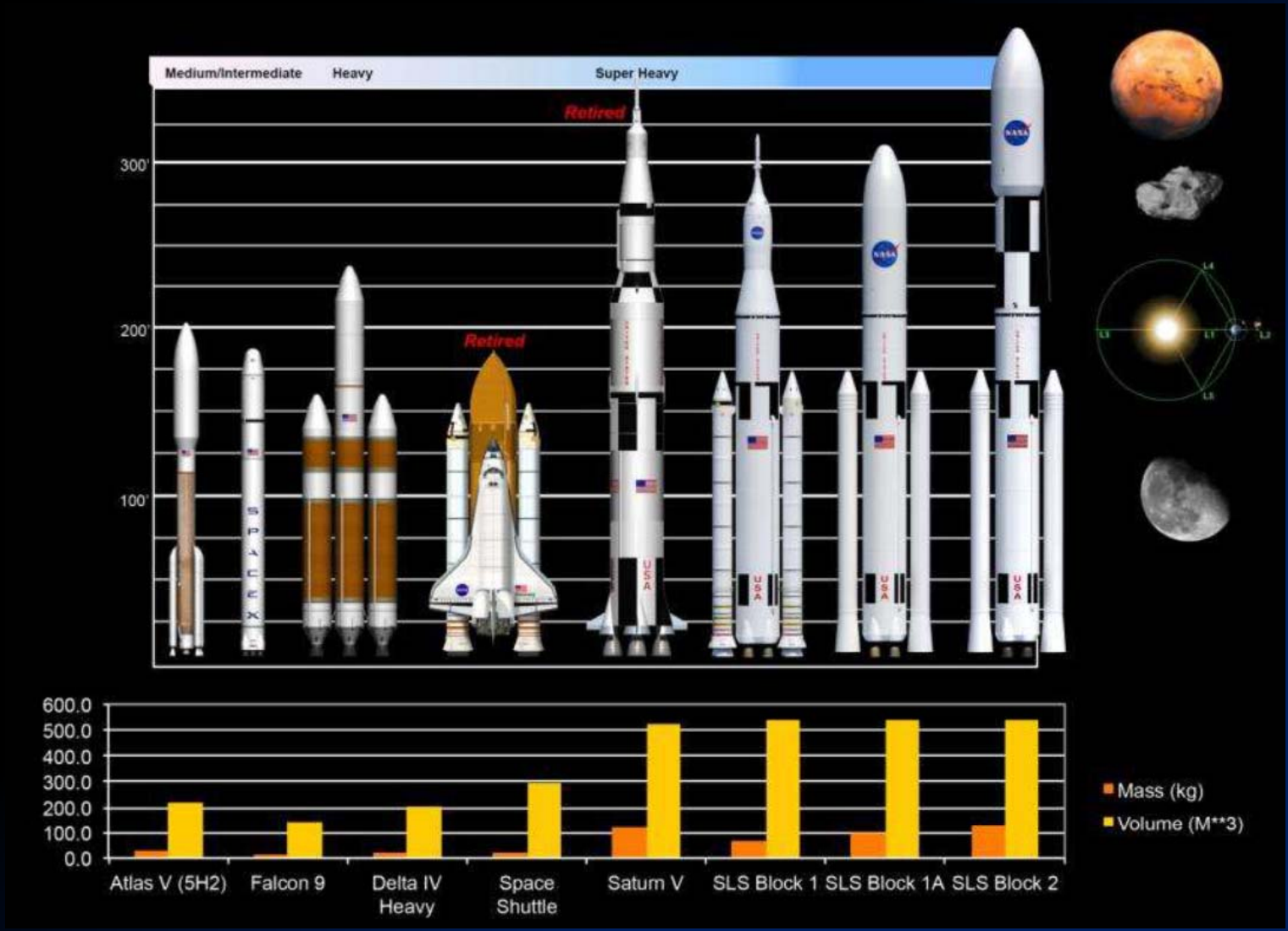
Benjamin Donahue
Boeing Defense, Space & Security

Space Launch System Capabilities

SLS Capabilities Open Exploration Mission Space For beyond LEO Missions 2020-2040

1. **SLS Payloads can Include:**
   - **-MPCV / Orion**
   - **-In-Space transfer stages**
   - **-Crew habitats (for transfer stages)**
   - **-Ascent, descent Stages**
   - **-Large space telescopes**
   - **-Large interplanetary spacecraft**
2. **These Payloads enable Crew Missions to the Lagrange Points, Moon, Asteroids, Phobos and Mars, as well as high value Science Destinations like Europa and Titan**

Most Capable U.S. Launch Vehicle



Copyright © 2010 Boeing. All rights reserved.

SLS Family –

Heavy Lift for Beyond LEO Exploration Missions

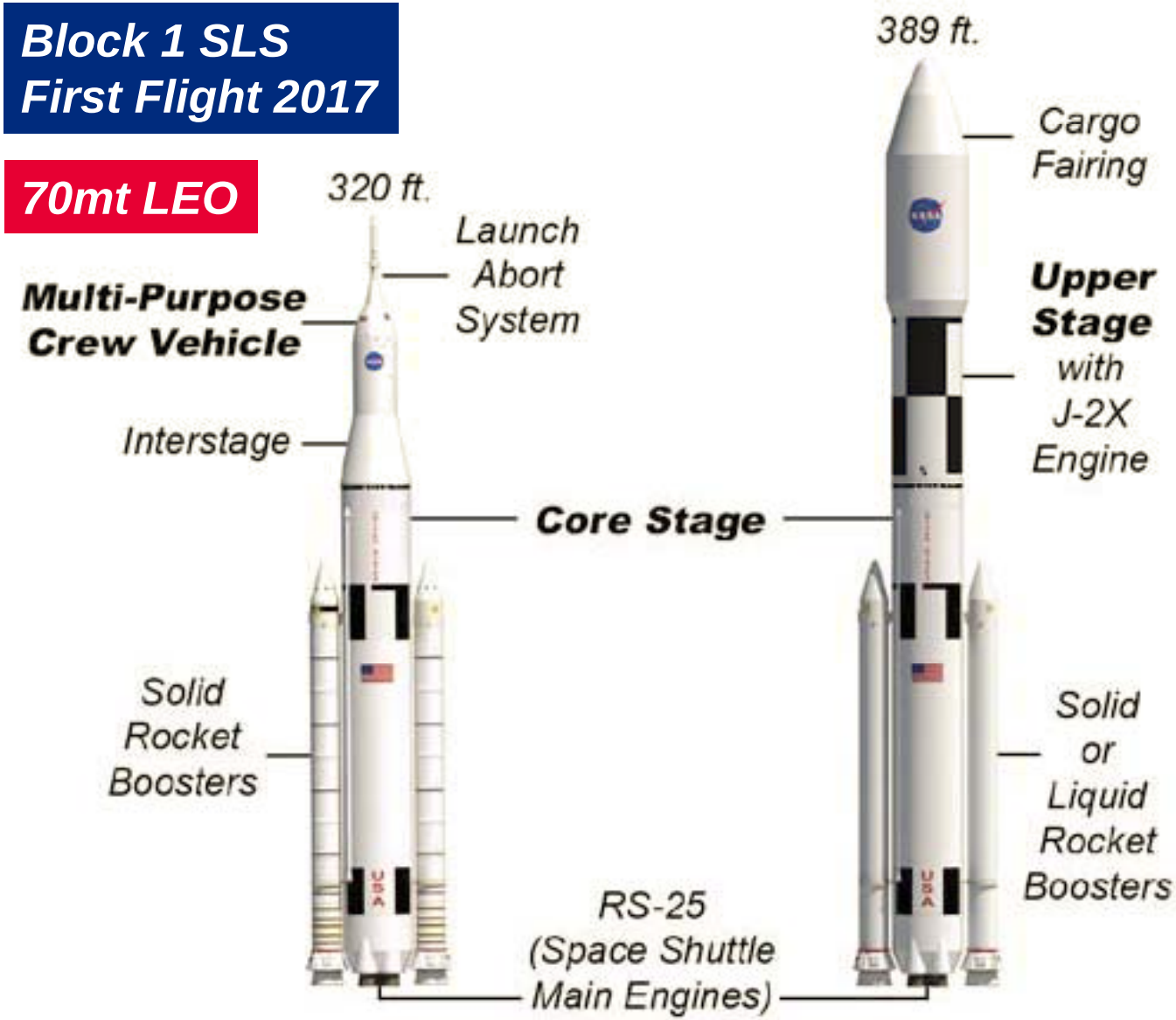
Block 1 SLS
First Flight 2017

70mt LEO

Evolved SLS
Block 2

130mt to LEO

8.4m diameter or 10.0 m Payload Fairing

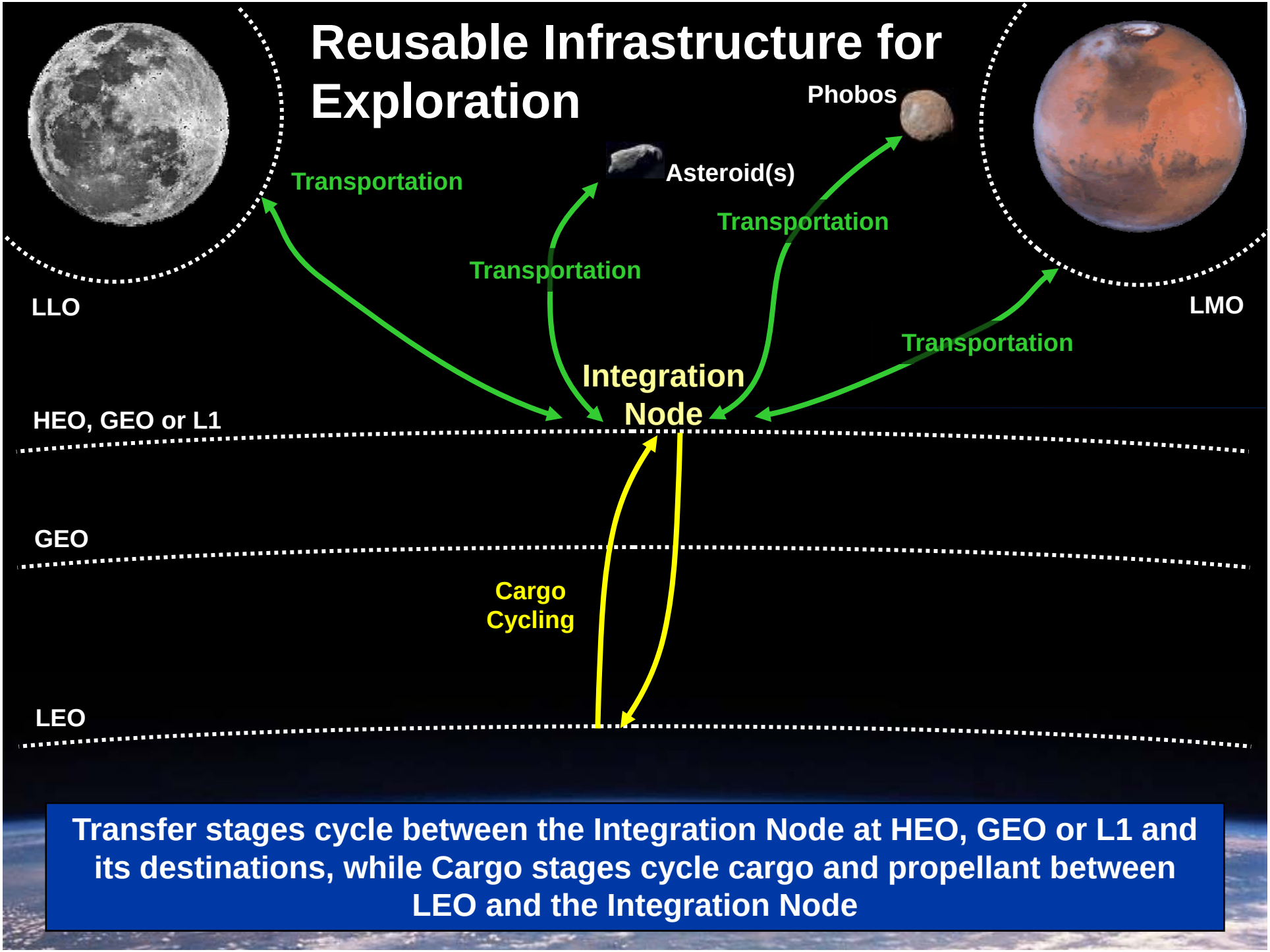


In-Space Transfer Systems

1. Design In-space stages to achievable missions 2020-40
2. Fit on SLS
3. Evolve in capability; Extensible
4. Consider both Crewed and Cargo missions
5. Abort capability for Crew Missions
6. Consider the 2033 “Easy Year” for Mars

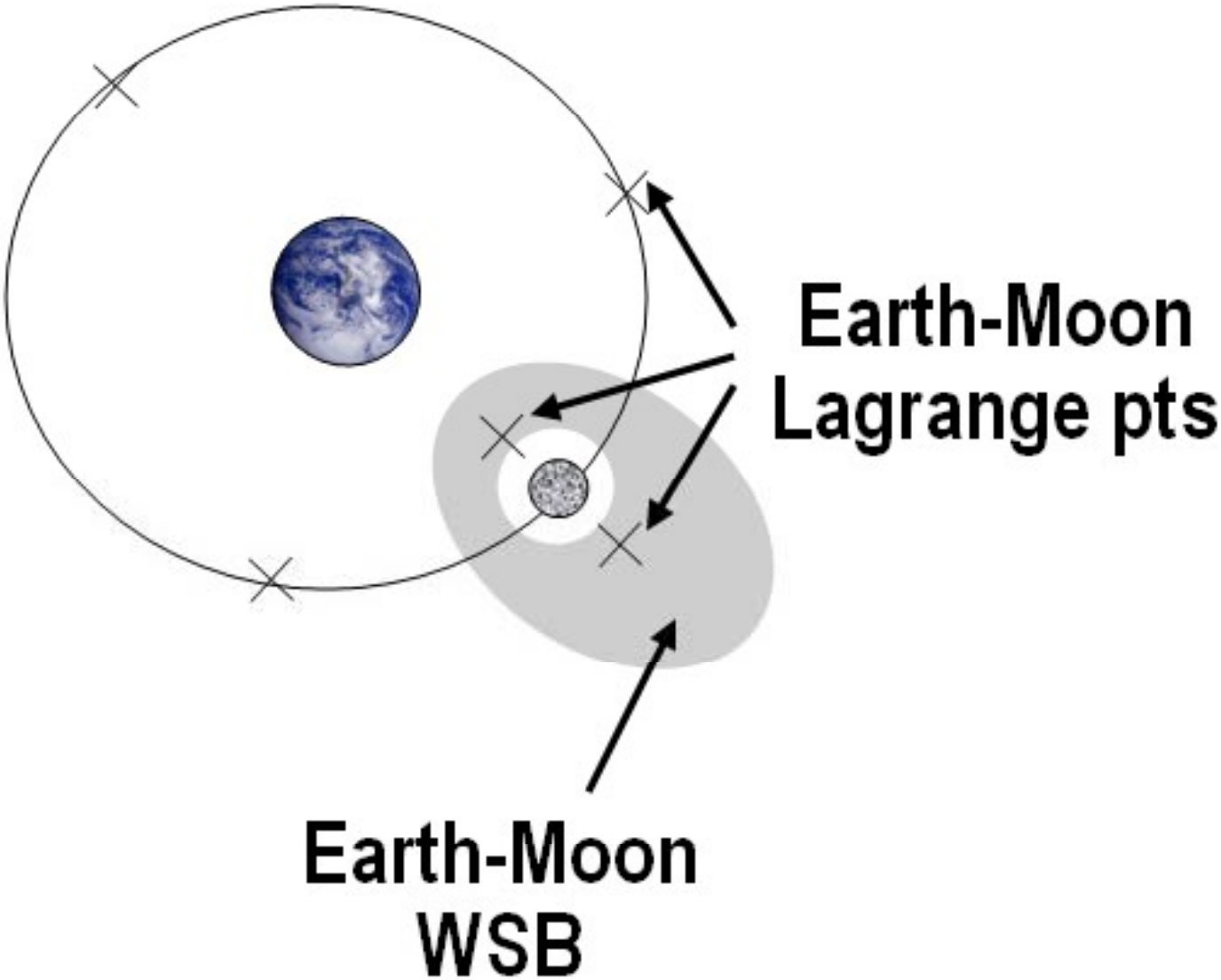
Copyright © 2010 Boeing. All rights reserved.

Reusable Infrastructure for Exploration



Transfer stages cycle between the Integration Node at HEO, GEO or L1 and its destinations, while Cargo stages cycle cargo and propellant between LEO and the Integration Node

Earth Moon L Points



Copyright © 2010 Boeing. All rights reserved.

Mission Destinations: Opportunities

E-Moon L-Point Based, LEO Staging, SLS Direct Launch

E-Moon L-Point Based Missions

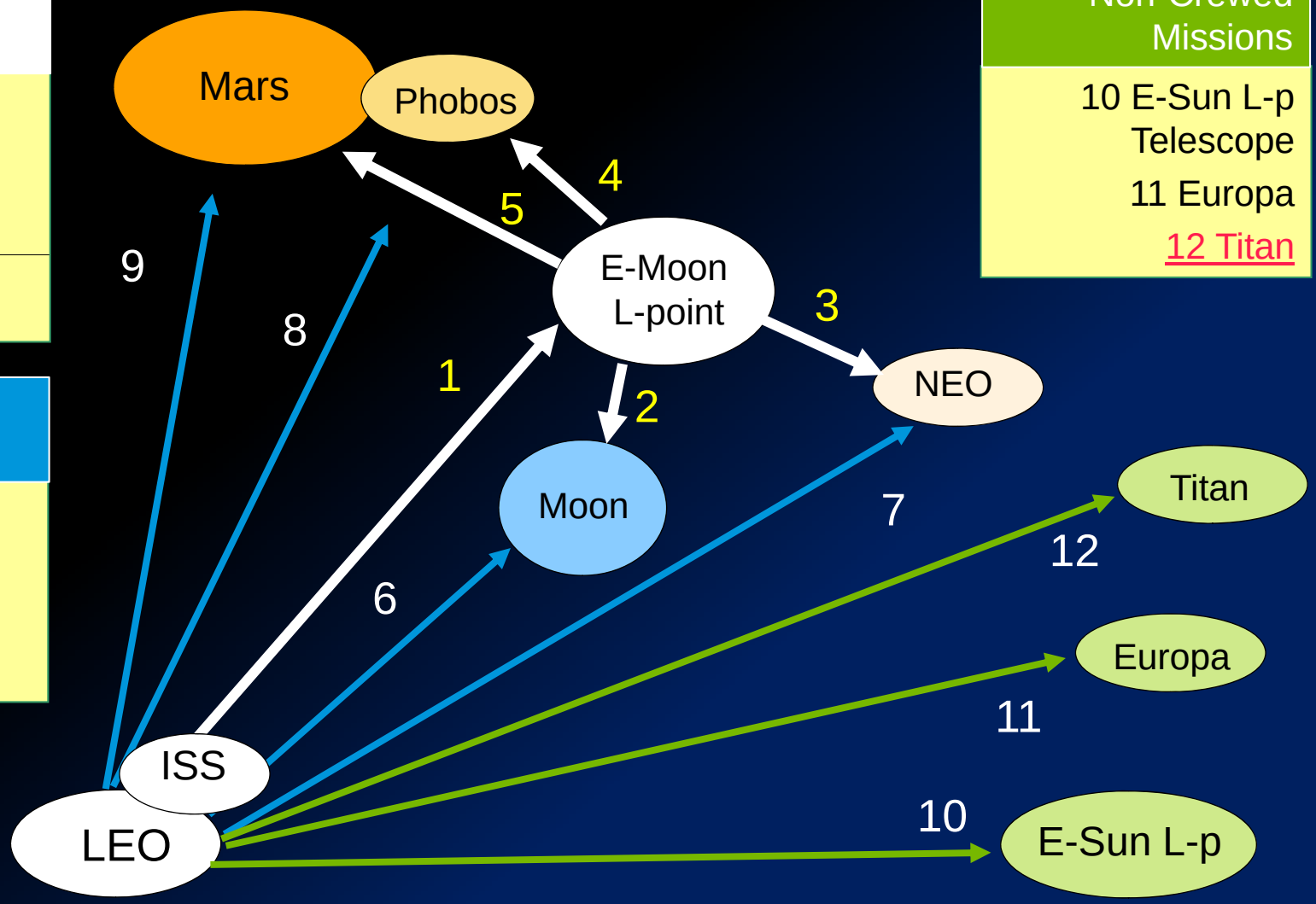
- 1 L-Point
- 2 Moon
- 3 NEO
- ~~4 Mars Phobos~~
- 5 Mars Surface

LEO Staged Missions

- 6 moon
- 7 NEO
- 8 Phobos
- 9 Mars Surface

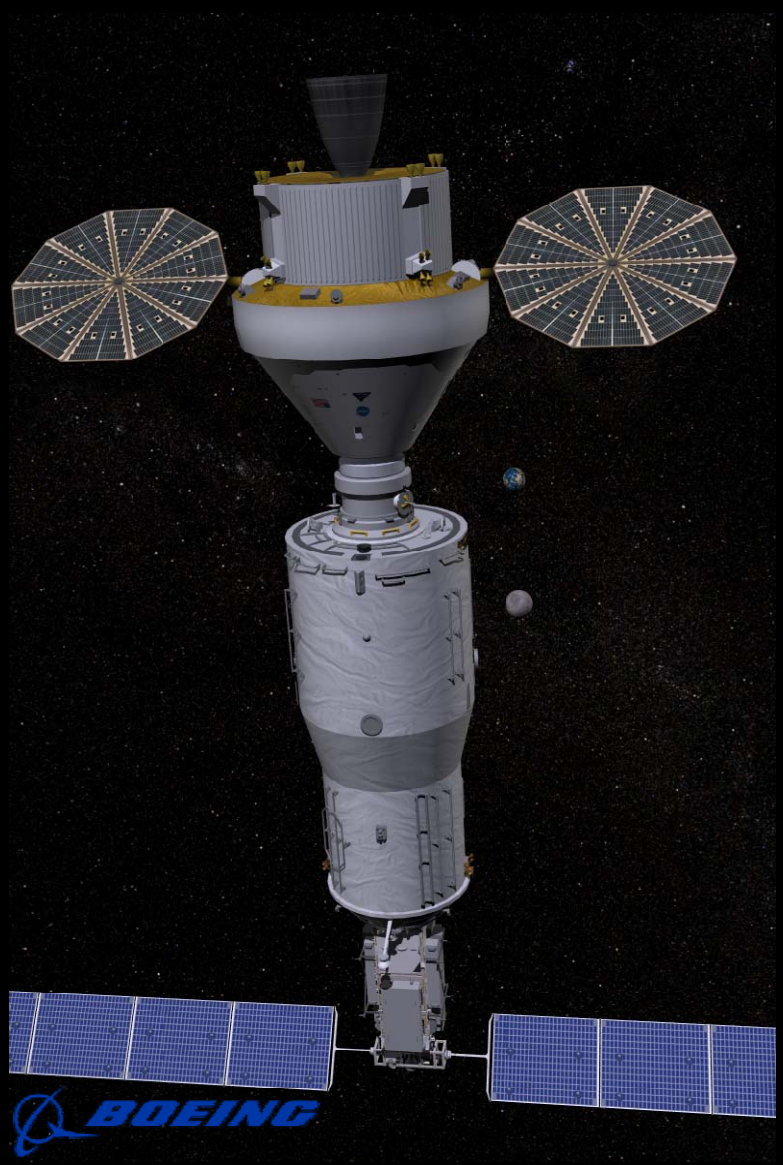
Non-Crewed Missions

- 10 E-Sun L-p Telescope
- 11 Europa
- 12 Titan



Copyright © 2010 Boeing. All rights reserved.

Mission Basing from L-Point Node

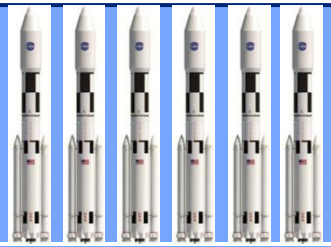


Architectures Based from L-Point Waypoints

1. Utilizing *E-Moon Libration point (EMLP) Platform* as Waypoint for transfer stages allows flexibility in Architecture Design
2. EMLP Station allows Lunar sorties utilizing a *reusable lander*; reducing recurring costs.
3. With key propulsion, habitation and other technologies *proven in near-Earth space*, extended duration missions to Phobos and Mars can follow.
4. Reusable E-Mars transfer stages reduce recurring costs for Crew Mars missions
5. Operations & technologies demonstrated for Lunar program extended to Mars campaign
6. The *two linked architectures* (Moon and Mars) facilitate a stepwise progression enabled by the SLS.

Stepwise Progression to Destinations

Mars



Mars Surface Mission
Paylds: (In addition to Phobos Set)
- Mars Crew Lander (Ascent Stg)
- Mars Cargo Lander (Surface Hab)
- Aeroshell for Lander(s)

Phobos

Phobos Crewed Mission (Low Mars Orbit)
Payloads: (no Lander required)
- Mars Transfer Stage + Chemical Kick Stage
- Crew Habitat (Transit)
- MPCV / Orion

NEO

NEO Crewed Mission
Payloads:
- MPCV/ Orion (x 2)
- Chemical Transfer Stage(s)

Moon

"1 SLS per Crew Sortie" Lunar Missions
Payloads:
- MPCV / Orion
- Lander Propellant
- Lunar Surface payloads

L1 L2

Emplace EMLP Platform
Payloads:
- Crew Habitat
- Power Module

Emplace Reusable Lander
Payloads:
- MPCV/ Orion
- Reusable Lunar Lander

Copyright © 2010 Boeing. All rights reserved.

Step 1 in Progression
-Emplace EMLP Platform

Mars

Mars Surface Mission
Paylds: (In addition to Phobos Set)
- Mars Crew Lander (Ascent Stg)
- Mars Cargo Lander (Surface Hab)
- Aeroshell for Lander(s)

Phobos

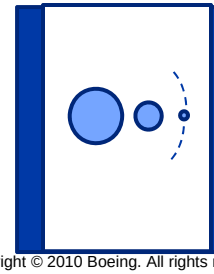
Phobos Crewed Mission (Low Mars Orbit)
Payloads: (no Lander required)
- Mars Transfer Stage + Chemical Kick Stage
- Crew Habitat (Transit)
- MPCV / Orion

NEO

NEO Crewed Mission
Payloads:
- MPCV/ Orion (x 2)
- Chemical Transfer Stage

Moon

"1 SLS per Crew Sortie" Lunar Missions
Payloads:
- MPCV / Orion
- Lander Propellant
- Lunar Surface payloads



L1
L2

Emplace EMLP Platform
Payloads:
- **Crew Habitat**
- **Docking Module**
- **Power Module**

Emplace Reusable Lander
Payloads:
- MPCV/ Orion
- Reusable Lunar Lander

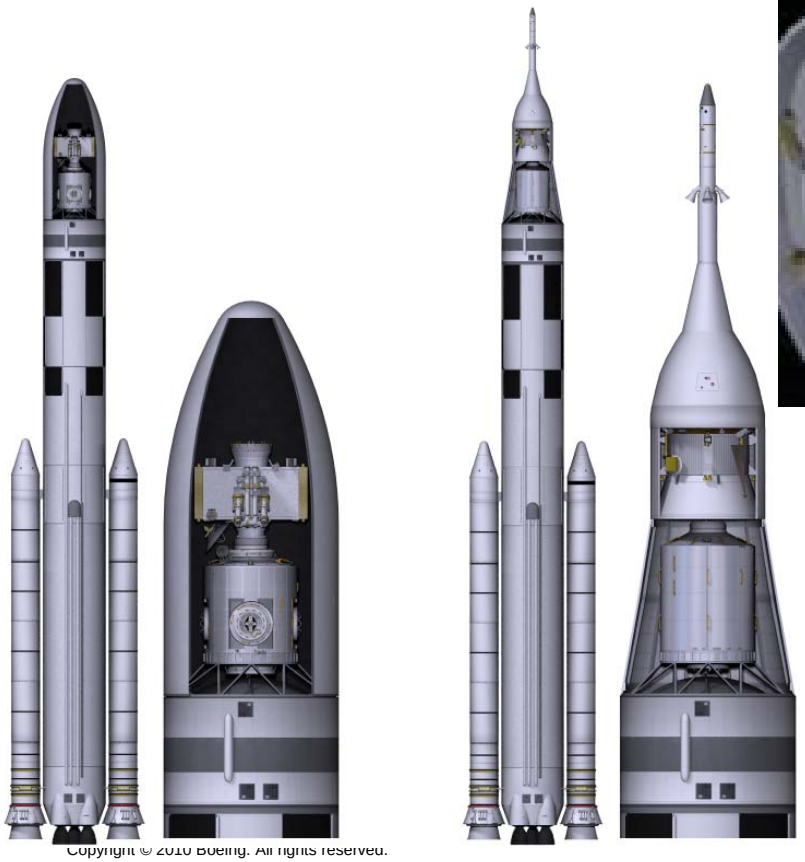
Copyright © 2010 Boeing. All rights reserved.

SLS Launch of L-Point Modules

Two Launches of Evolved SLS

Defense, Space & Security
Space Exploration

- **The Platform could be launched directly to EML2 with *two SLS launches***



Operations Hub for beyond LEO Missions

1. **Base for reusable Lunar lander**
2. **2.5 days from Moon**
3. **Real time teleoperation of robotic assets on Lunar surface**
4. **Refurbishment center for Lunar lander**
5. **Outside of debris environment**

Copyright © 2010 Boeing. All rights reserved.

Step 2: Emplace Reusable Lander at Node

-One Launch of Evolved SLS

Mars

Mars Surface Mission
Paylds: (In addition to Phobos Set)
- Mars Crew Lander (Ascent Stg)
- Mars Cargo Lander (Surface Hab)
- Aeroshell for Lander(s)

Phobos

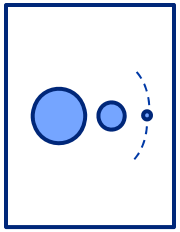
Phobos Crewed Mission (Low Mars Orbit)
Payloads: (no Lander required)
- Mars Transfer Stage + Chemical Kick Stage
- Crew Habitat (Transit: outbound and inbound)
- MPCV / Orion

NEO

NEO Crewed Mission
Payloads:
- MPCV/ Orion (x 2)
- Chemical Transfer Stage

Moon

"1 SLS per Crew Sortie" Lunar Missions
Payloads:
- MPCV / Orion
- Lander Propellant
- Lunar Surface payloads



L1
L2

Emplace E-Moon L-Point Platform
Payloads:
- Crew Habitat
- Power Module

Emplace Reusable Lander
Payloads:
- **MPCV/ Orion**
- **Reusable Lunar Lander**

Copyright © 2010 Boeing. All rights reserved.

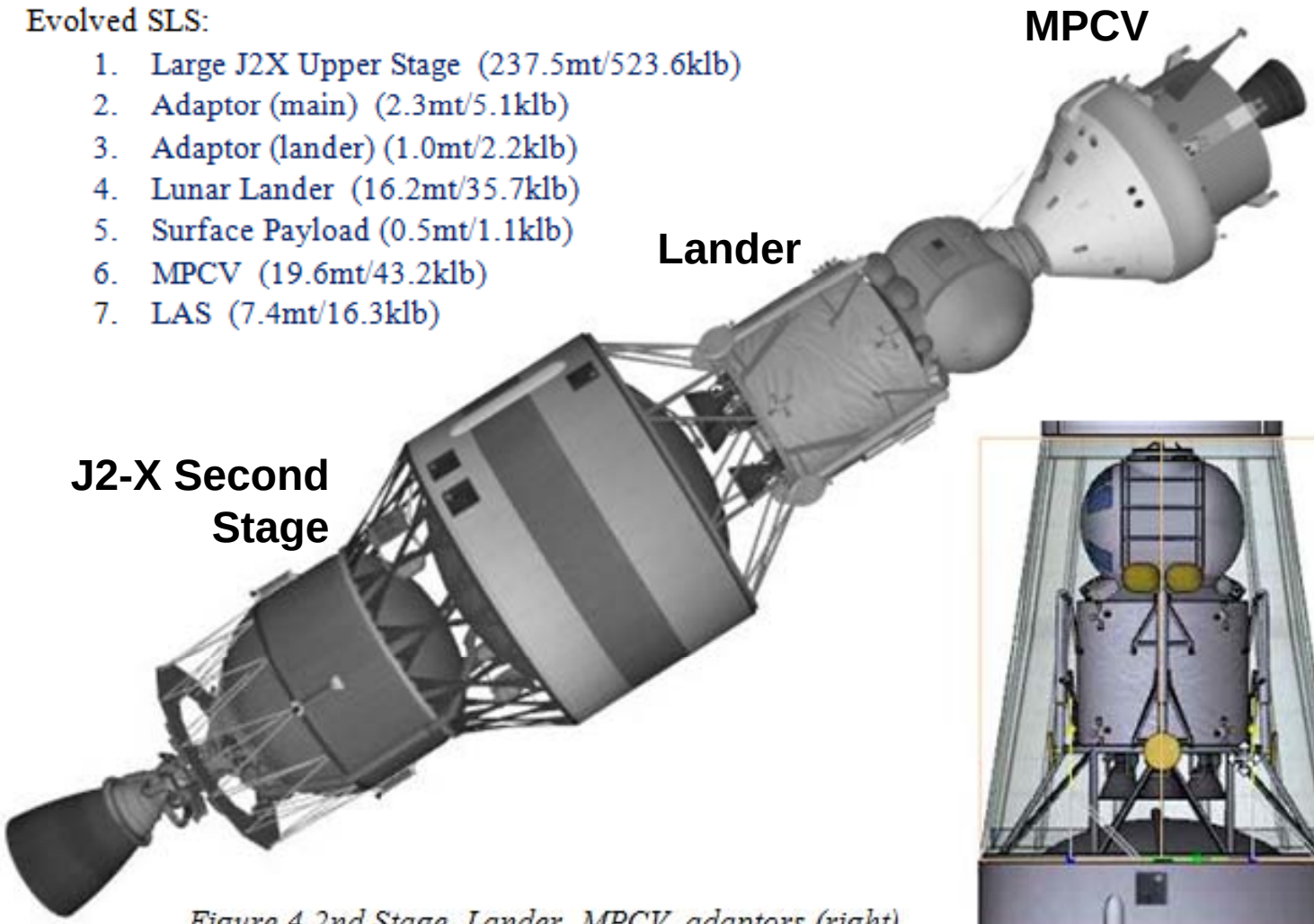
SLS Launched Reusable Lunar Lander

Shown with MPCV / Orion in Route to EMLP

Elements for Lunar Mission 2

Evolved SLS:

1. Large J2X Upper Stage (237.5mt/523.6klb)
2. Adaptor (main) (2.3mt/5.1klb)
3. Adaptor (lander) (1.0mt/2.2klb)
4. Lunar Lander (16.2mt/35.7klb)
5. Surface Payload (0.5mt/1.1klb)
6. MPCV (19.6mt/43.2klb)
7. LAS (7.4mt/16.3klb)



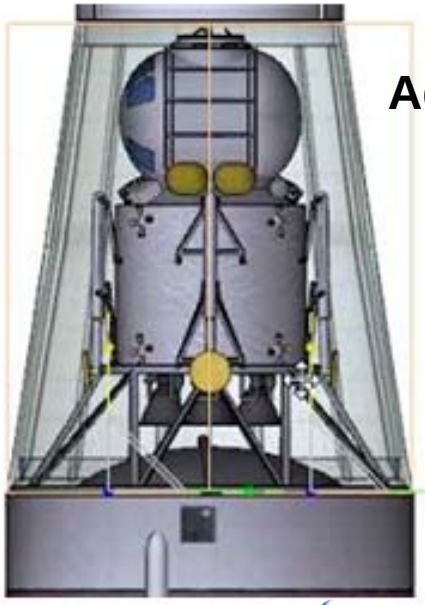


Figure 4 2nd Stage, Lander, MPCV, adaptors (right)

Copyright © 2010 Boeing. All rights reserved.

SLS Launch Details

SLS Stage Parameters and Payloads

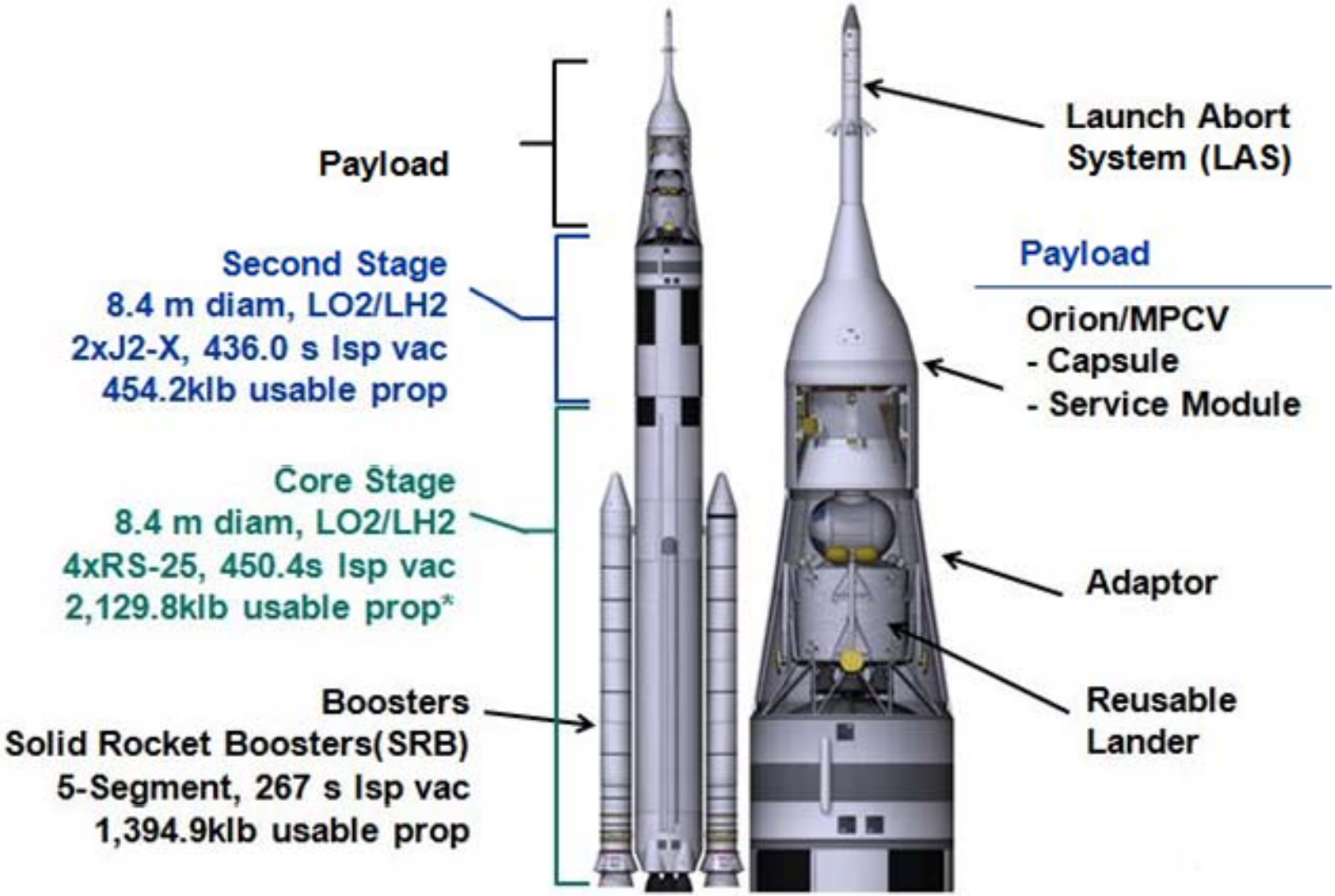


Figure 5 Evolved SLS with Lander and MPCV as Payloads

Step 3: Crew Sorties to Surface

-One SLS Evolved Launch per Sortie

Mars

Mars Surface Mission
Paylds: (In addition to Phobos Set)
- Mars Crew Lander (Ascent Stg)
- Mars Cargo Lander (Surface Hab)
- Aeroshell for Lander(s)

Phobos

Phobos Crewed Mission (Low Mars Orbit)
Payloads: (no Lander required)
- Mars Transfer Stage + Chemical Kick Stage
- Crew Habitat (Transit)
- MPCV / Orion

NEO

NEO Crewed Mission
Payloads:
- MPCV/ Orion (x 2)
- Chemical Transfer Stage

Moon

"1 SLS per Crew Sortie" Lunar Missions

Payloads:
- **MPCV / Orion**
- **Lander Propellant**
- **Lunar Surface payloads**

L1
L2

Emplace E-Moon L-Point Platform
Payloads:
- Crew Habitat
- Power Module

Emplace Reusable Lander
Payloads:
- MPCV/ Orion
- Reusable Lunar Lander

Copyright © 2010 Boeing. All rights reserved.

SLS Launched In-Space Stage

with MPCV in Route to EMLP: 1 SLS Launch

Elements for Lunar Mission 3

Evolved SLS:

1. Large J2X Upper Stage (237.5mt/523.6klb)
2. Adaptor (2.3mt/5.1klb)
3. In-space stage (75.4mt/166.2klb)
4. MPCV (19.6mt/43.2klb)
5. Surf payloads (0.5mt/1.1klb)
6. LAS (7.4mt/16.3klb)

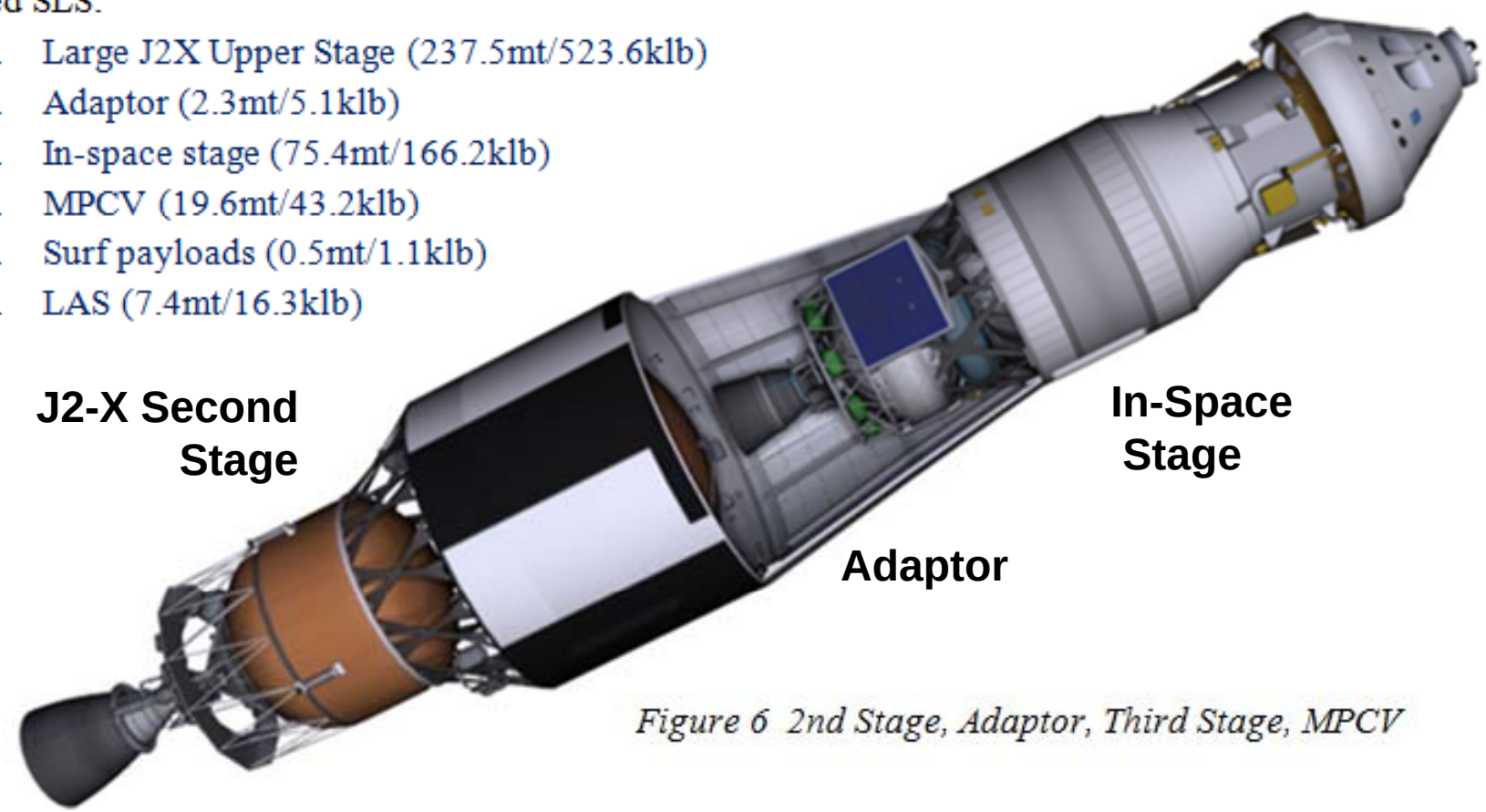


Figure 6 2nd Stage, Adaptor, Third Stage, MPCV

Copyright © 2010 Boeing. All rights reserved.

In-Space Stage with Lander

Legs Stowed, Shown in Route to Moon

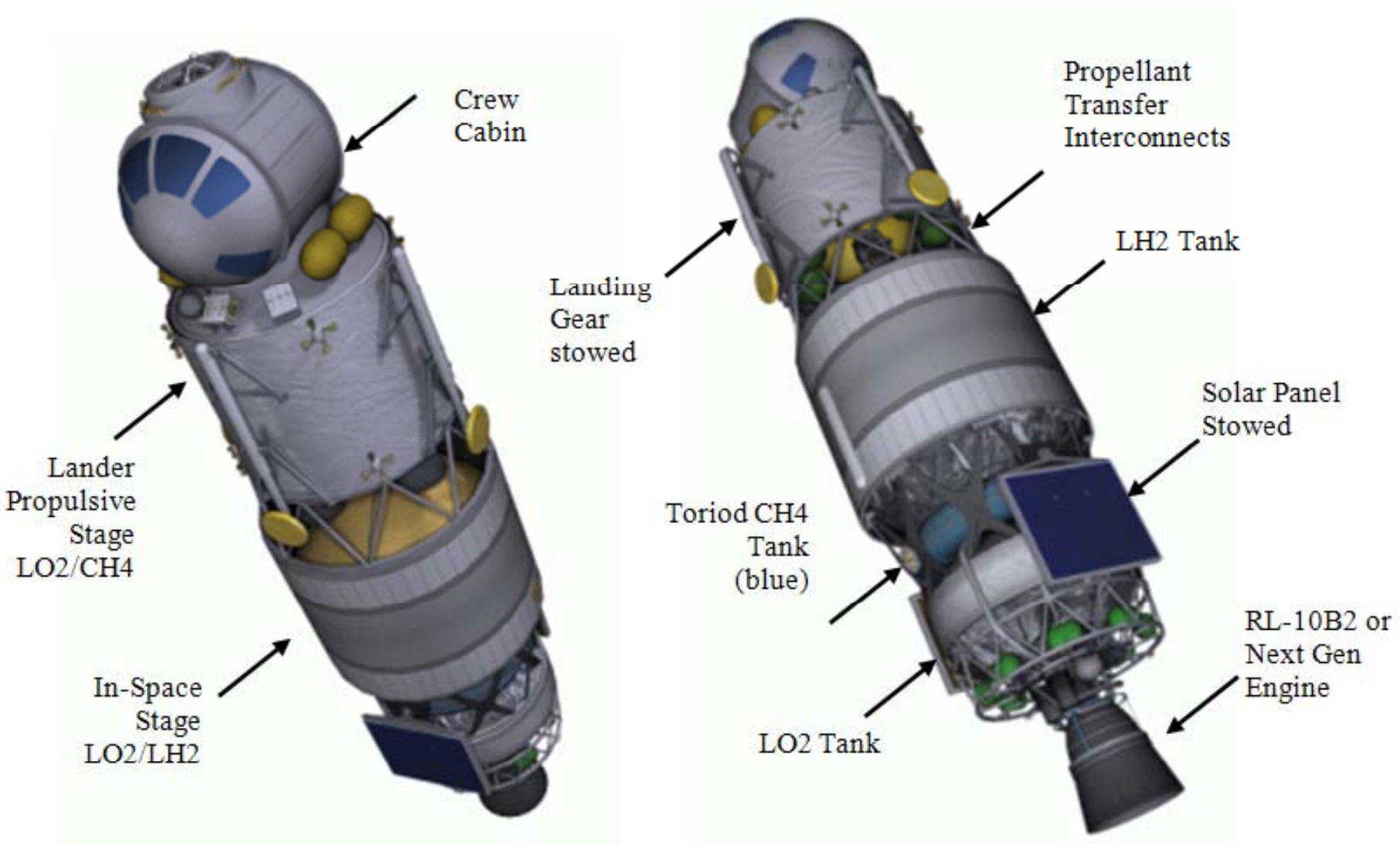


Figure 12 In-Space Stage and Lander during EMLP-to-Moon Transit

Single Stage, Reusable Lander: LO2/CH4

Returns to EMLP for Refueling and Reuse

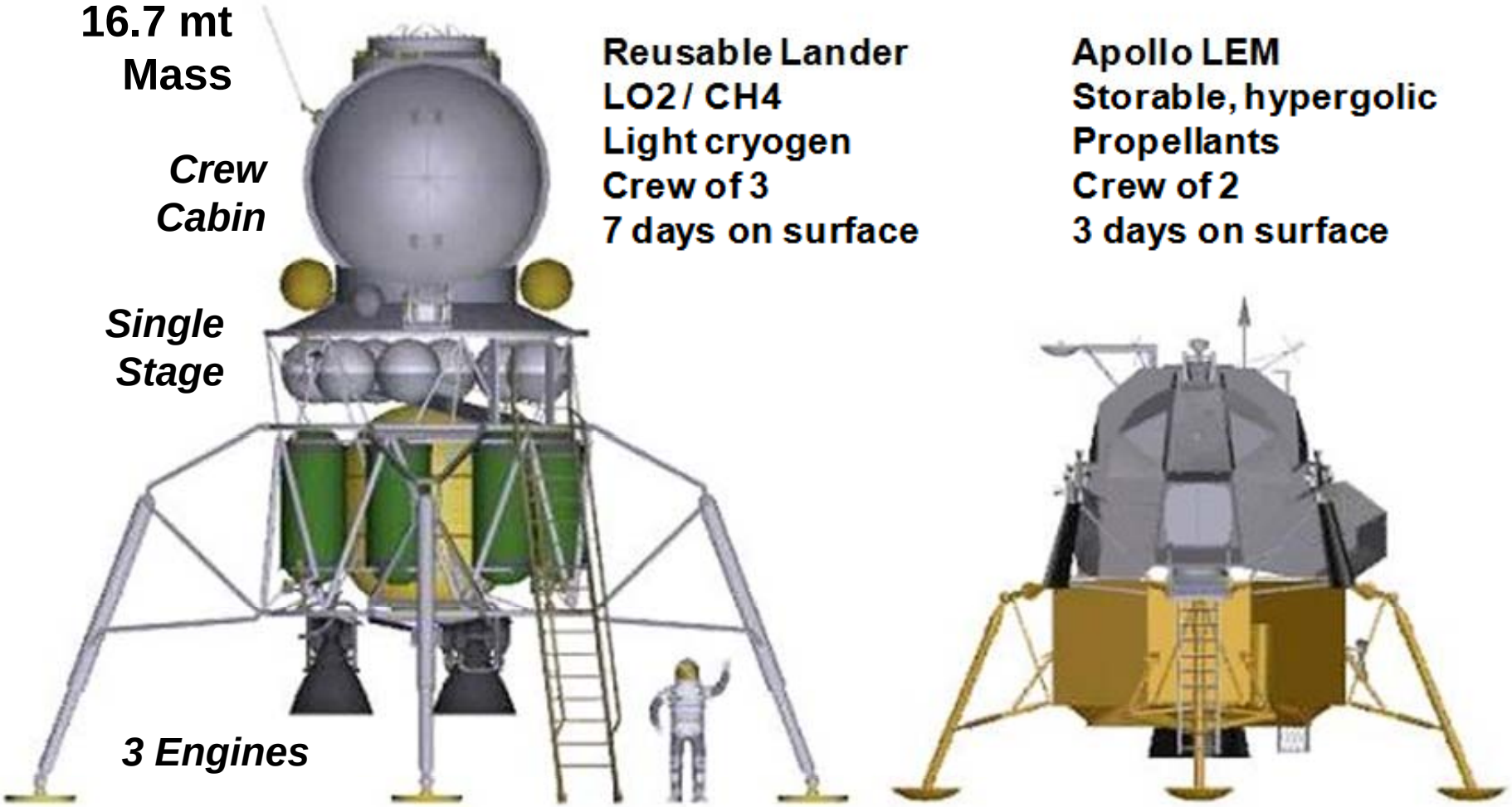
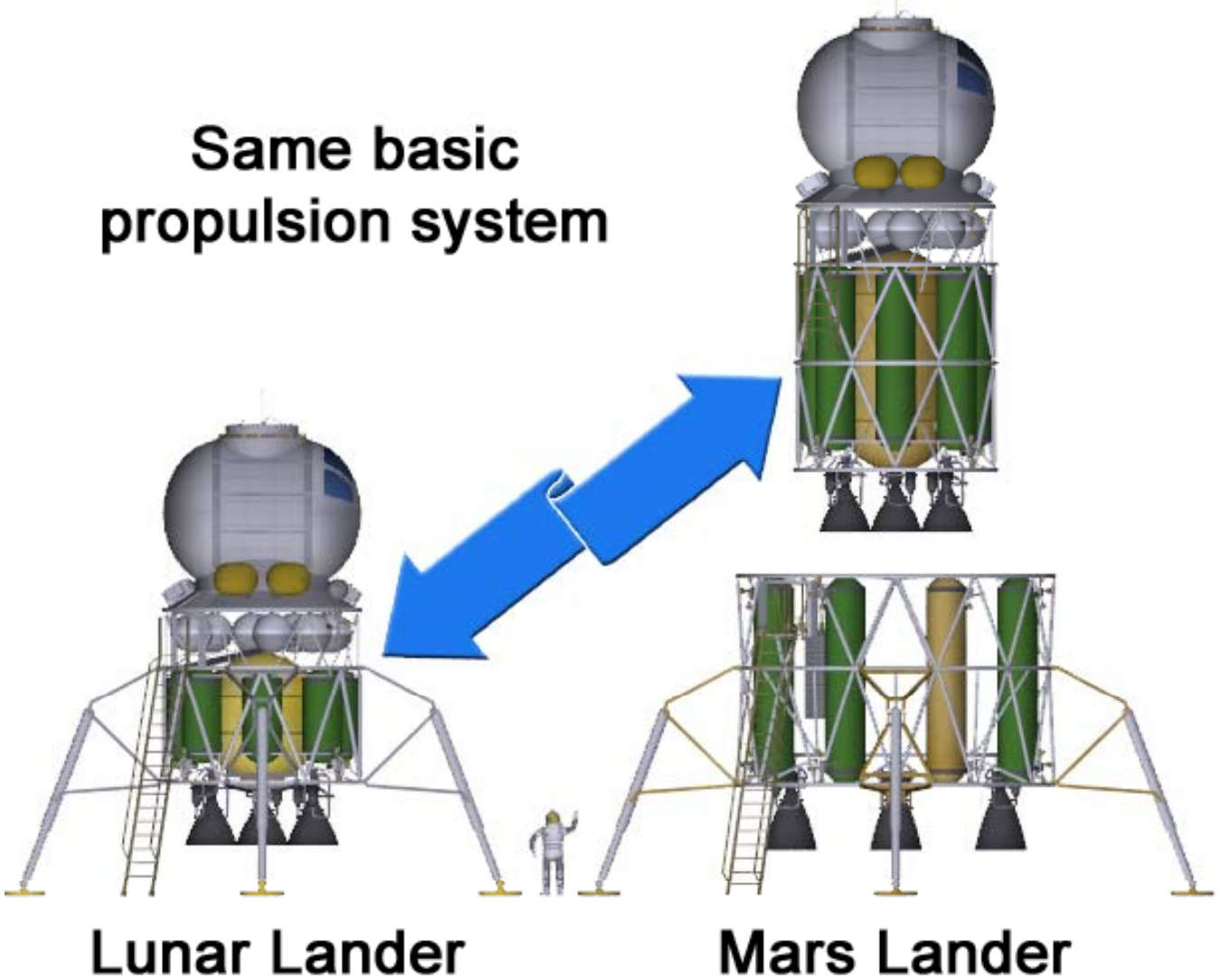


Figure 8 Reusable Lunar lander (Left) Size Comparison with Apollo LEM (Right)

Copyright © 2010 Boeing. All rights reserved.

Extensibility to Mars Ascent Stage

Mars Ascent Stage Derivative of Lunar Lander



Copyright © 2010 Boeing. All rights reserved.

Beyond the Moon: NEO and Mars

1. Higher dV

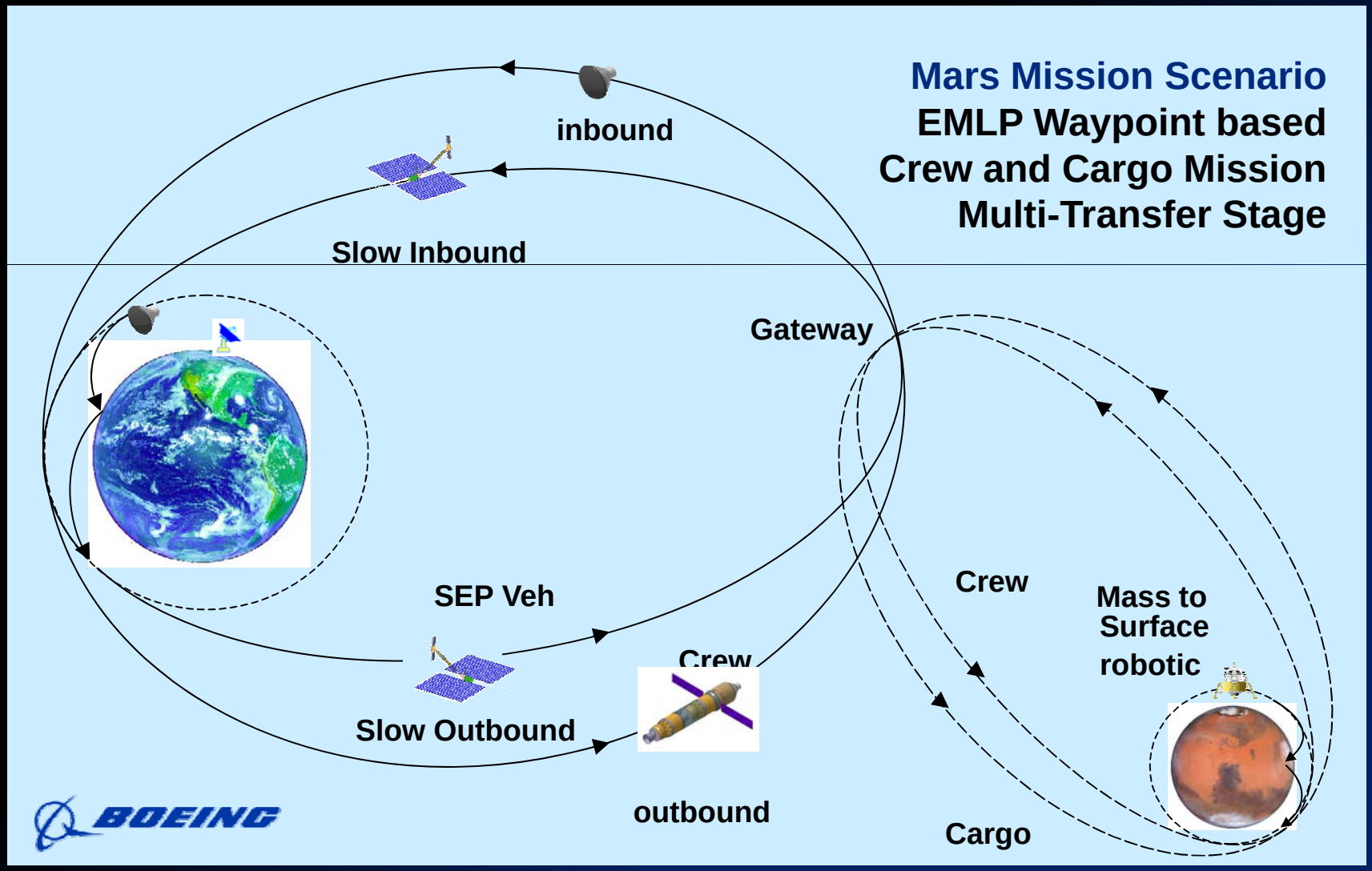
2. Heavier Payloads (Crew habitats, landers)

3. Longer Duration (2.5 years, Mars Conjunction, consumables)

4. Radiation protection

Copyright © 2010 Boeing. All rights reserved.

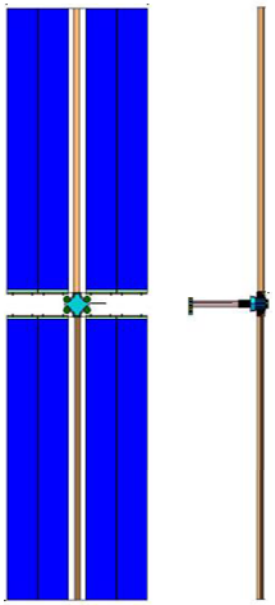
EML-point Based Mars Mission:
Extension of Lunar Mission Concept



Copyright © 2010 Boeing. All rights reserved.

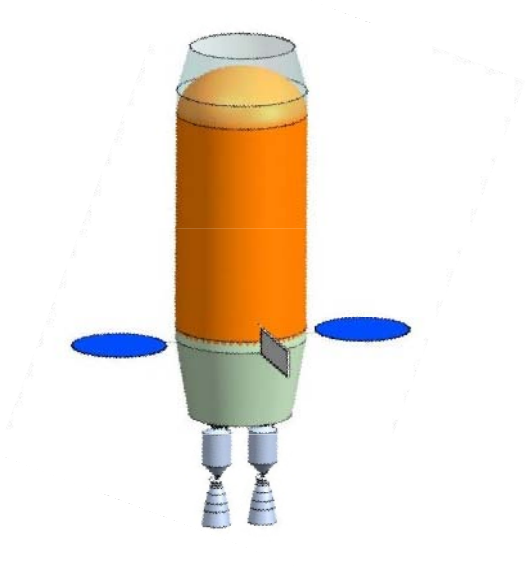
E-Mars Crew Transport Options

Solar Electric, Nuclear Thermal, Chemical Propulsion



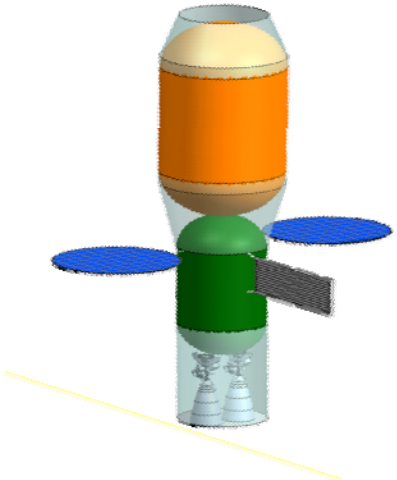
SEP Transfer Stage

- 800 kW power at 1 AU
- Reusable up to 5 trips
- Isp = 3000-4000 s



NTP Transfer Stage

- 20,000 lbf engine (2x)
- Leverages NERVA design
- Isp = 900 s



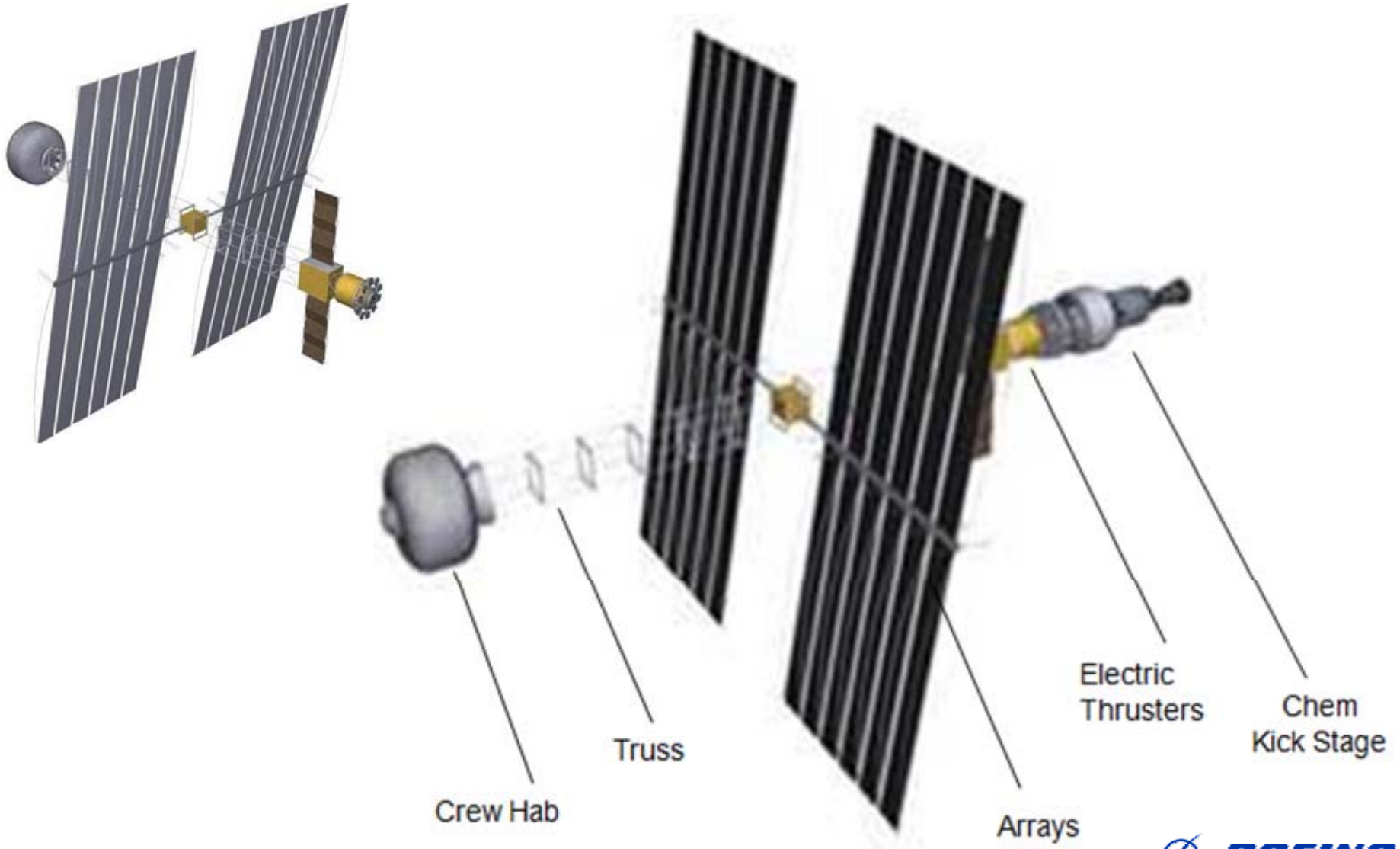
Cryo Transfer Stage

- O2/H2 engines
- Isp = 465 s

Copyright © 2010 Boeing. All rights reserved.

SEP Transfer Stage Archetype

Hab, Truss, Array, EP Thrusters, Optional Chemical Kick Stage



Copyright © 2010 Boeing. All rights reserved.

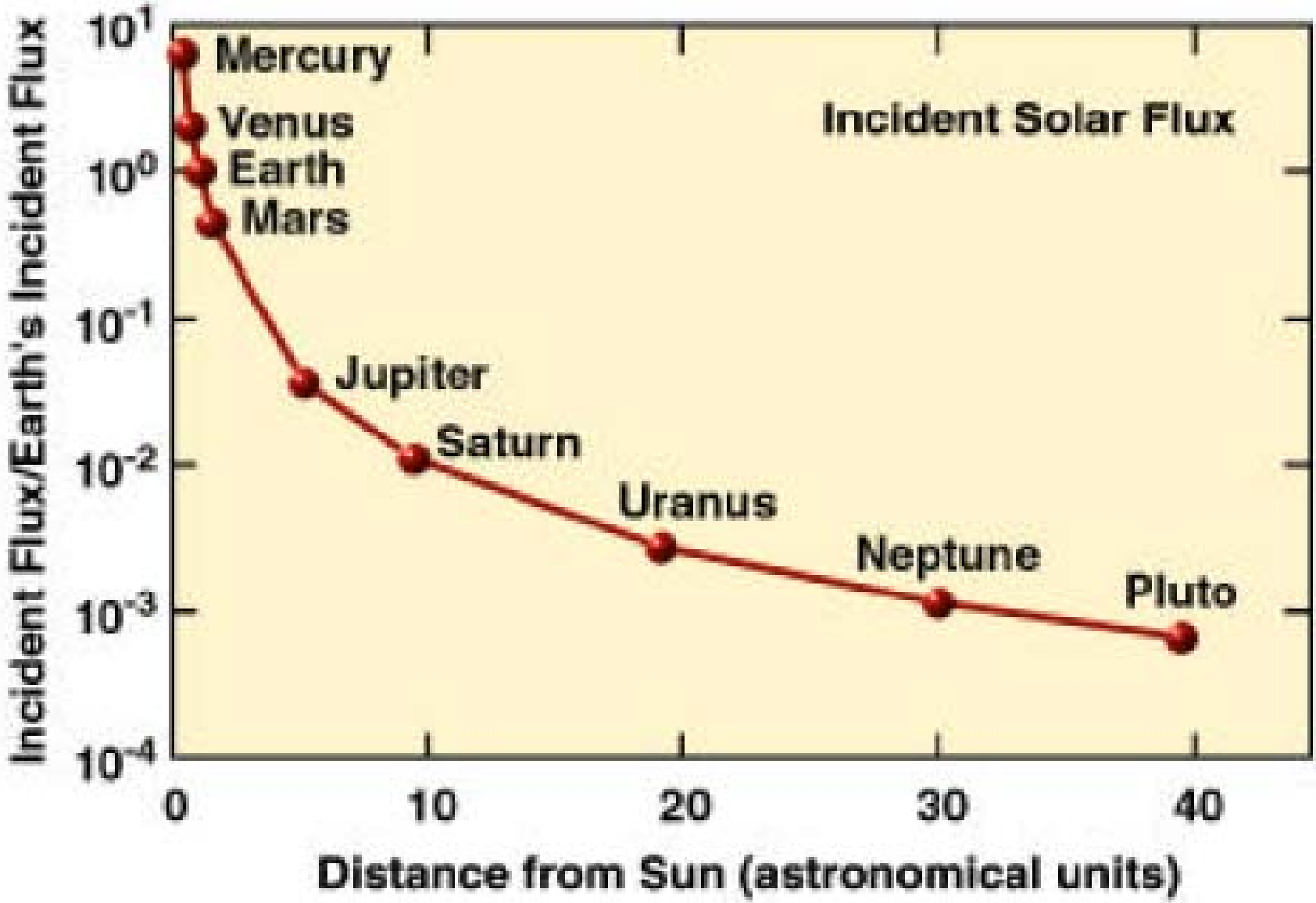
SEP Characteristics

1. +EP: High Isp (mass efficient) (most LV mass prop)
2. +Cell efficiency: getting higher each year
3. +Solar Flux: High Earth-Mars, always on
4. +Arrays: radiation resistant, dense packaging in LV
5. +Modular growth in power level
6. +Reusable, +ComSats: EP; arrays in production, 15y Life
7. +Graceful degradation modes (thruster, array panel)
8. -Low thrust -trip times f(power) +cargo, +add kick stage
9. -Not much flux at beyond Mars / Jovian distances –Nuclear
10. -Large arrays, -cell cost +concentator arrays

Copyright © 2010 Boeing. All rights reserved.

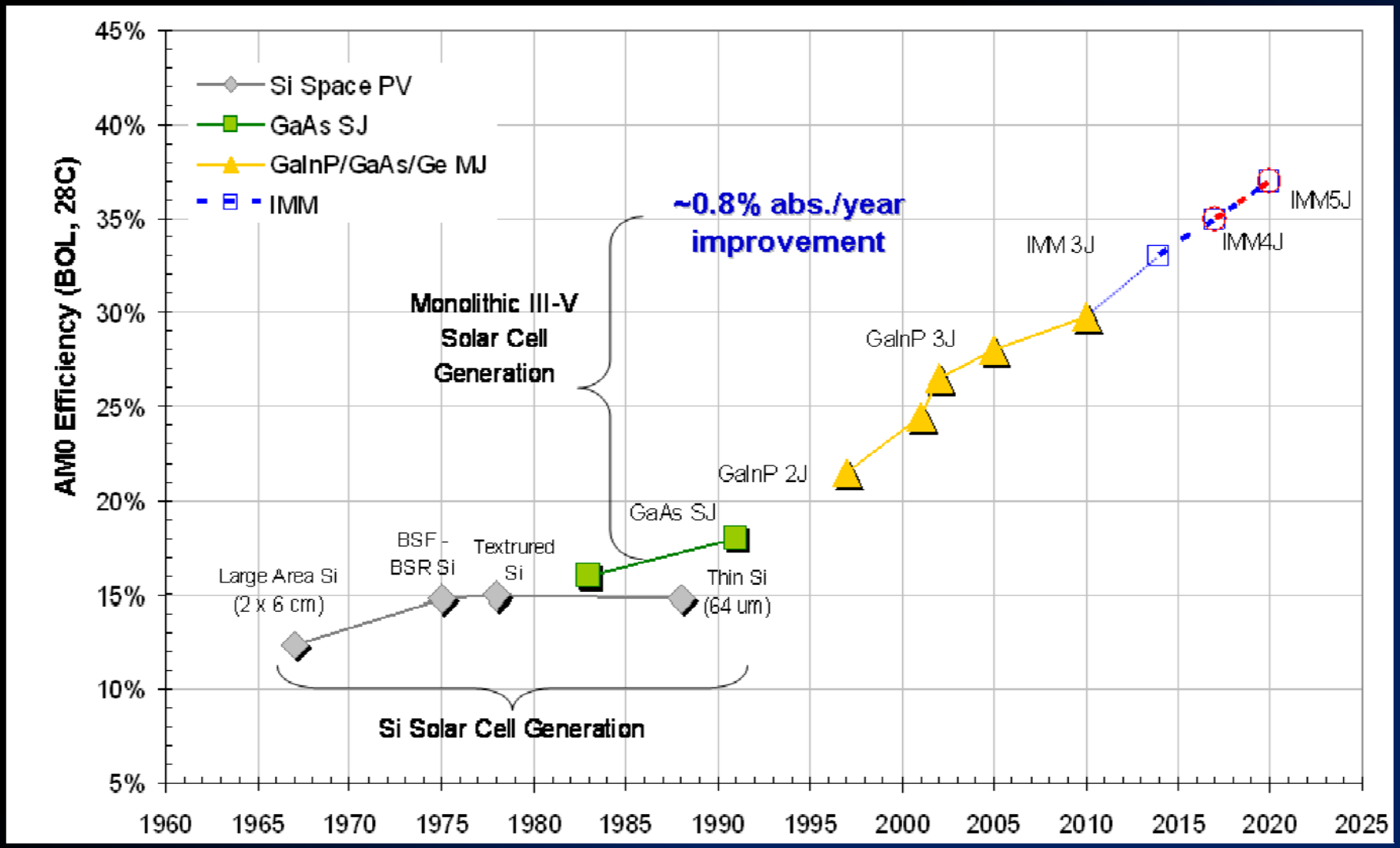
Solar Flux vs Distance From Sun

Mars ~40% flux of Earth



Solar Cell Efficiency Growth vs Year

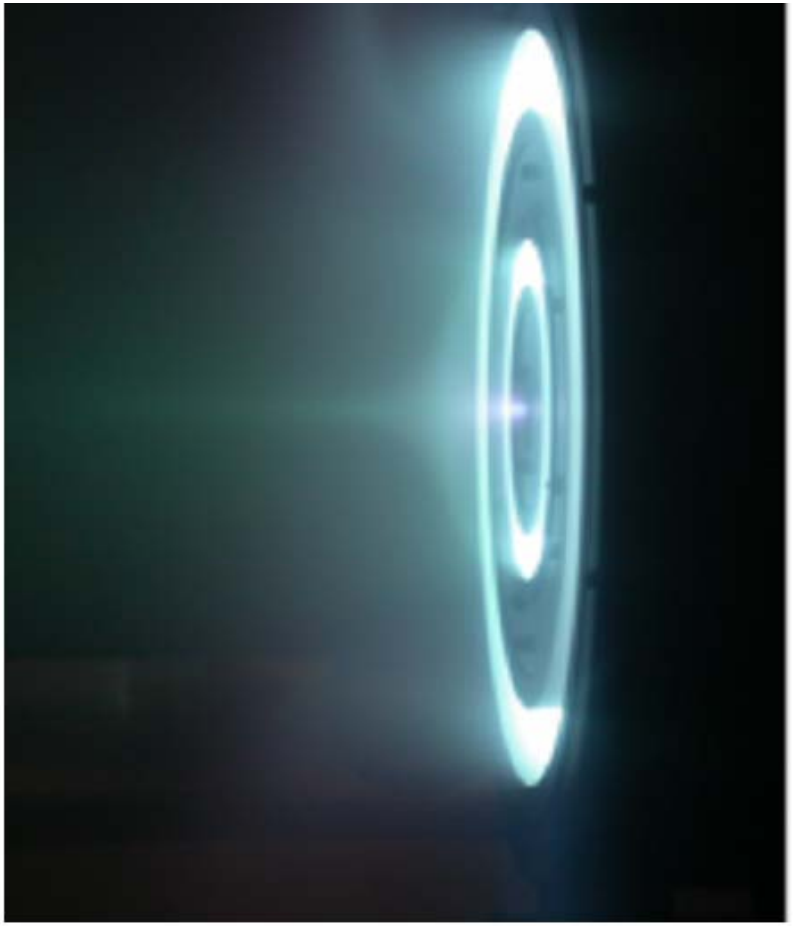
Averages ~0.8% per year improvement



Copyright © 2010 Boeing. All rights reserved.

Concentric Channel Hall Effect Thruster

Propellants: Xenon, Krypton, Argon: Variable Isp



-Variable Isp: 1300 – 5000 Secs Isp
-High Power: 100 - 200 kW per Thruster
-Dual Mode Operation

Courtesy AFRL

Copyright © 2010 Boeing. All rights reserved.

Step 4: NEO Missions:

-Intermediate Mission Duration: ~1 year

Mars

Mars Surface Mission
Paylds: (In addition to Phobos Set)
- Mars Crew Lander (Ascent Stg)
- Mars Cargo Lander (Surface Hab)
- Aeroshell for Lander(s)

Phobos

Phobos Crewed Mission (Low Mars Orbit)
Payloads: (no Lander required)
- Mars Transfer Stage + Chemical Kick Stage
- Crew Habitat (Transit)
- MPCV / Orion

NEO

NEO Crewed Mission
Payloads:
- MPCV/ Orion
- Inflatable Habitat

Moon

"1 SLS per Crew Sortie" Lunar Missions
Payloads:
- **MPCV / Orion**
- **Lander Propellant**
- **Lunar Surface payloads**

L1
L2

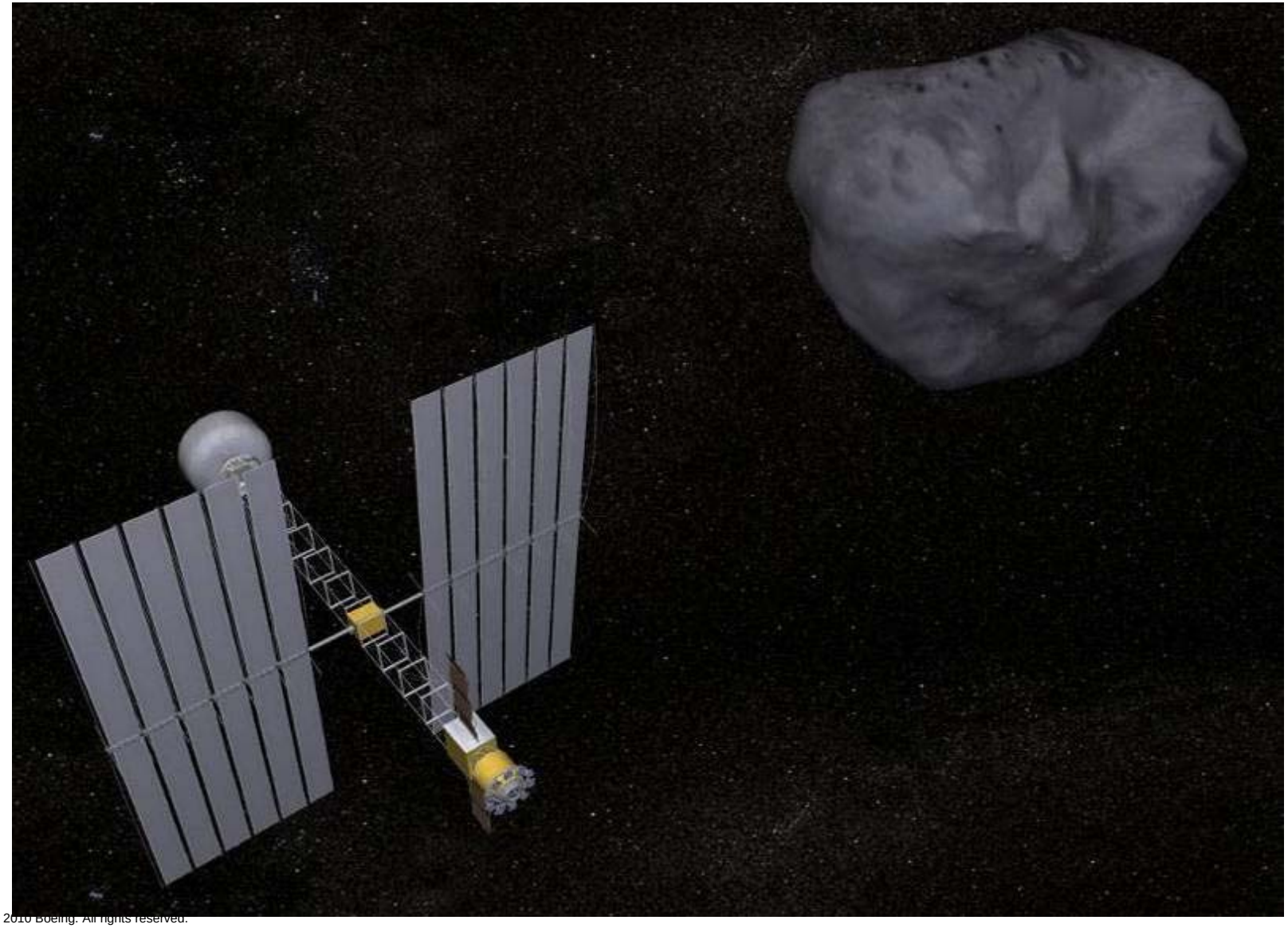
Emplace E-Moon L-Point Platform
Payloads:
- Crew Habitat
- Power Module

Emplace Reusable Lander
Payloads:
- MPCV/ Orion
- Reusable Lunar Lander

Copyright © 2010 Boeing. All rights reserved.

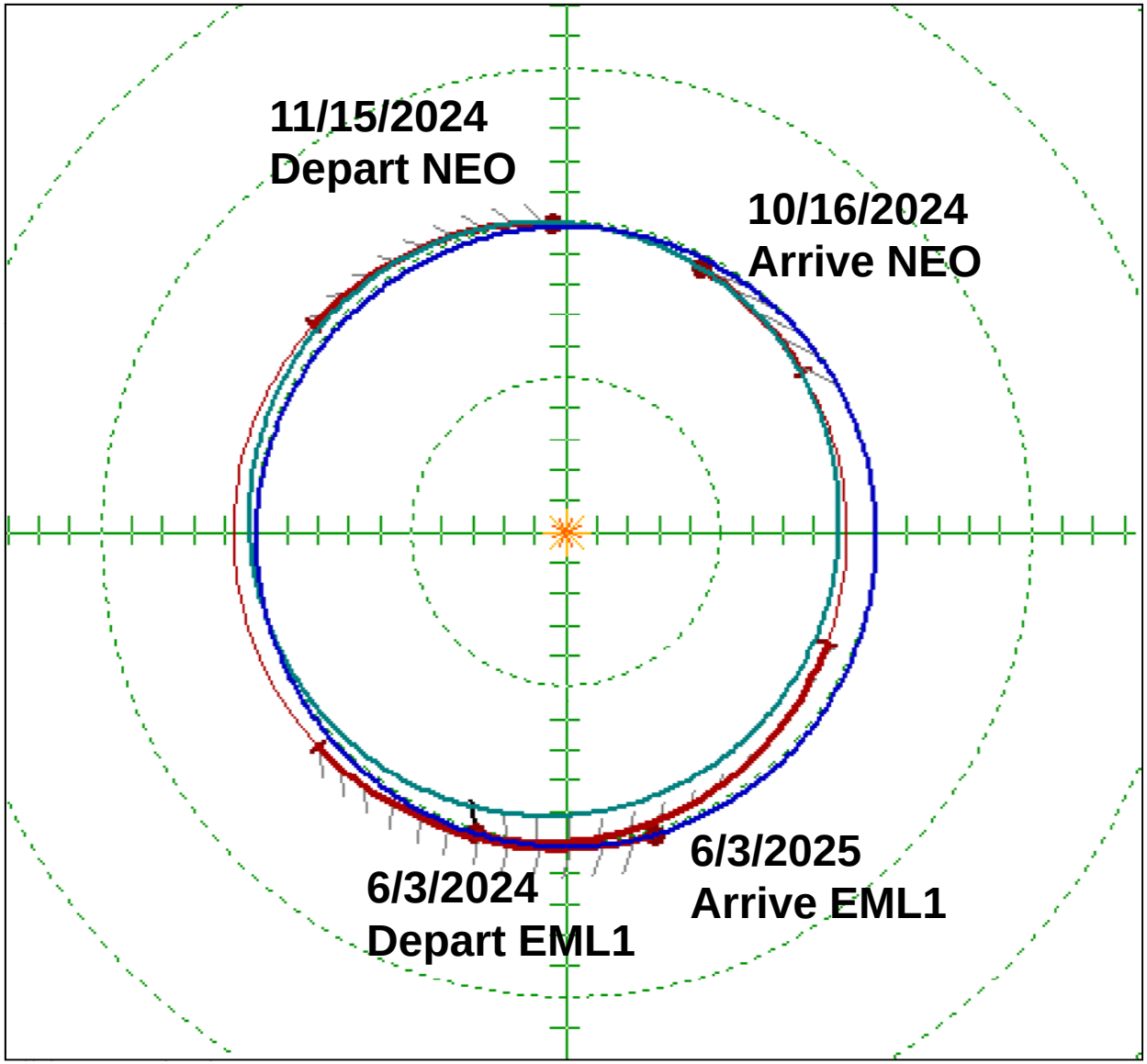
SEP Arrival at Near Earth Object

Mars precursor: ~2025: No Mars Gravity Well: No Lander



Copyright © 2010 Boeing. All rights reserved.

2008 EV5 NEO Mission Trajectory



- Transit to NEO takes about 4 months;
- Chemical kick stage used to shorten trip
- Approximately 30 days at NEO;
- Return trip about 7 months
- Overall trip takes ~ one year

Step 5: Crewed Phobos Mission

-Low Mars Orbit: First Visit to Mars

Mars

Mars Surface Mission
Paylds: (In addition to Phobos Set)
- Mars Crew Lander (Ascent Stg)
- Mars Cargo Lander (Surface Hab)
- Aeroshell for Lander(s)

Phobos

Phobos Crewed Mission (Low Mars Orbit)
Payloads: (*no Lander required*)
- **Mars Transfer Stage: *2.5 year Mission***
- **Chemical Kick Stage: *Initial Departure from EMLP***
- **Crew Habitat (Transit): *Crew of 4-5; Consumables***
- **MPCV / Orion**

NEO

NEO Crewed Mission
Payloads:
- MPCV/ Orion (x 2)
- Chemical Transfer Stage

Moon

"1 SLS per Crew Sortie" Lunar Missions
Payloads:
- MPCV / Orion
- Lander Propellant
- Lunar Surface payloads

Validates all Earth Mars Transfer Stage (MTV), Crew Habitation, Telemetry Systems. MTV and Hab Returned to EMLP, Reused.

L1
L2

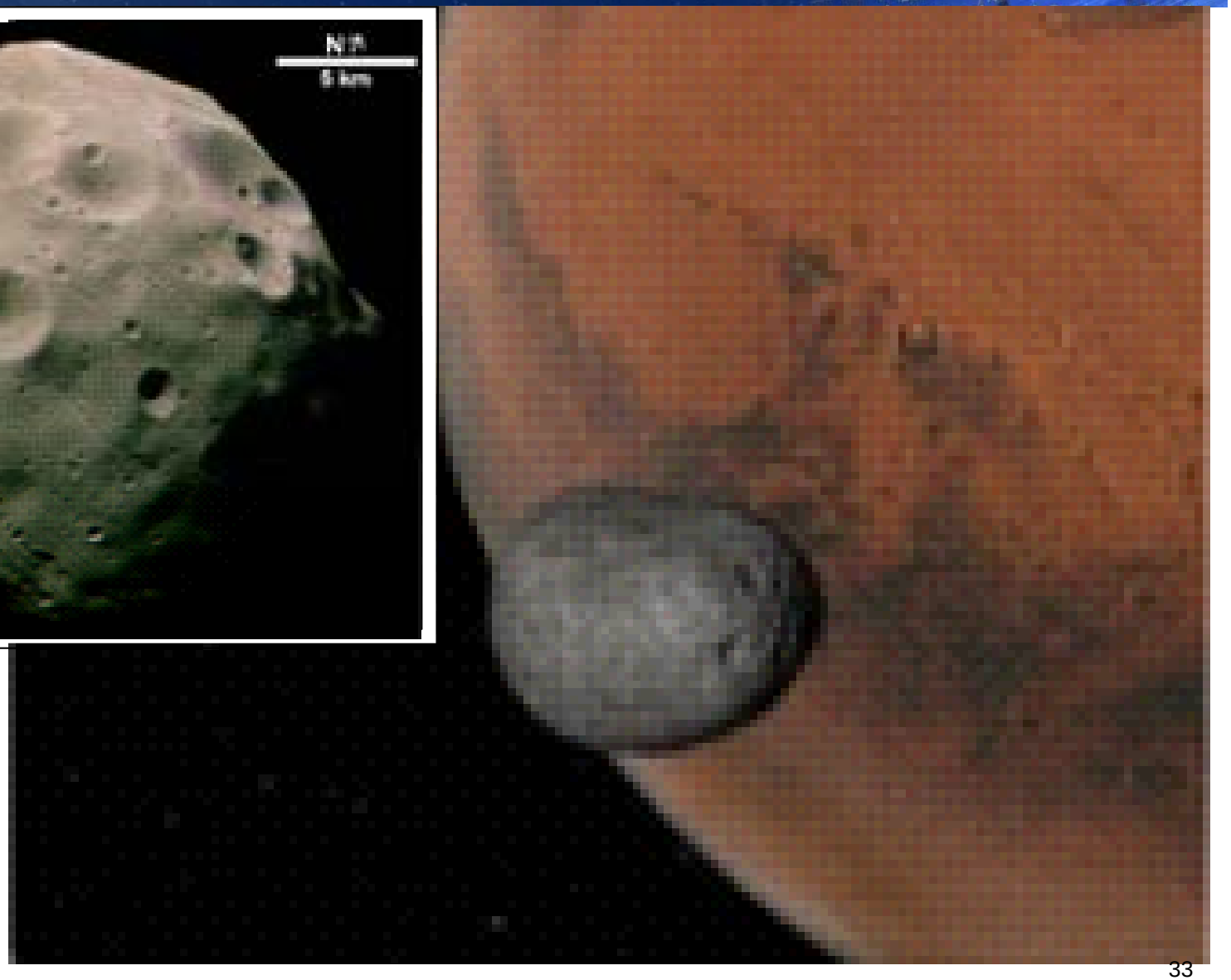
Emplace E-Moon L-Point Platform
Payloads:
- Crew Habitat
- Power Module

Emplace Reusable Lander
Payloads:
- MPCV/ Orion
- Reusable Lunar Lander

Copyright © 2010 Boeing. All rights reserved.

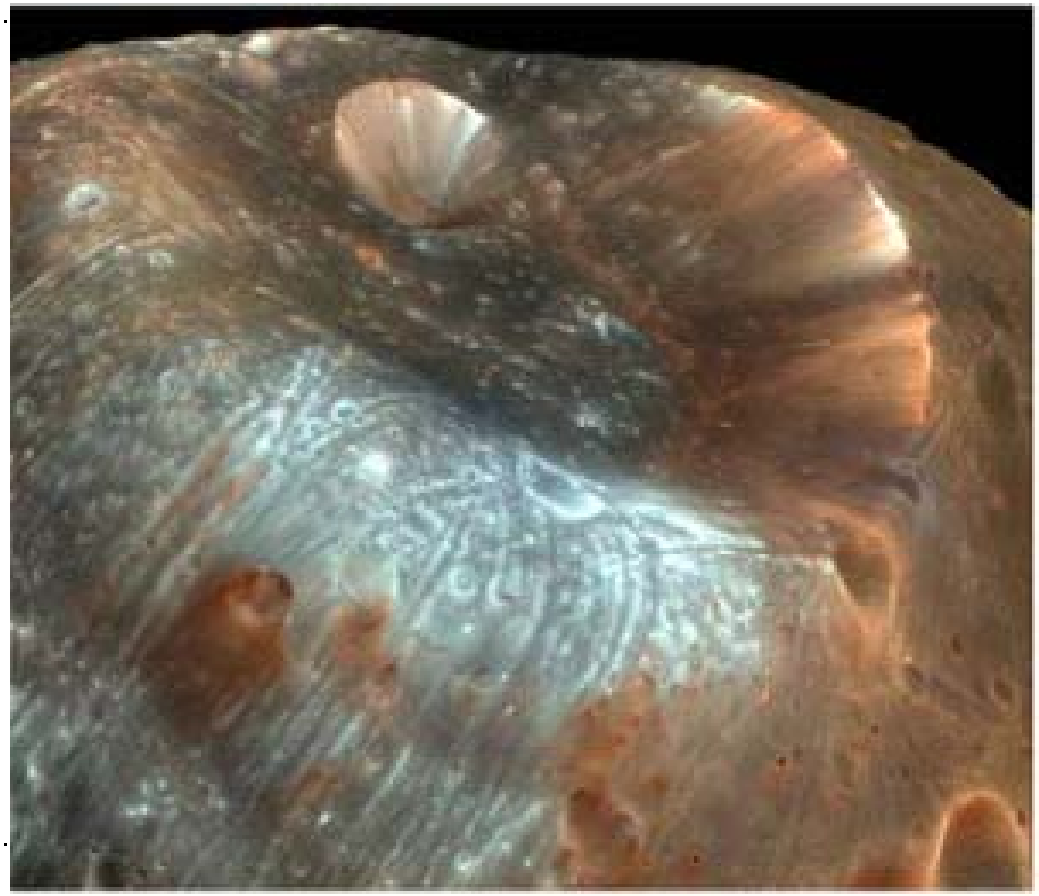
Phobos:

Orbits ~6000 km above Mars



Copyright © 2010 Boeing. All rights reserved.

Phobos Outpost:
One Side Always Faces Mars



False color image

Mars Transfer Stage maneuvers to the bottom of the *Stickney* crater.

The crew always have a view of Mars to teleoperate surface assets (rovers, science, and pilot plant systems) real time, EVA to explore Phobos surface.

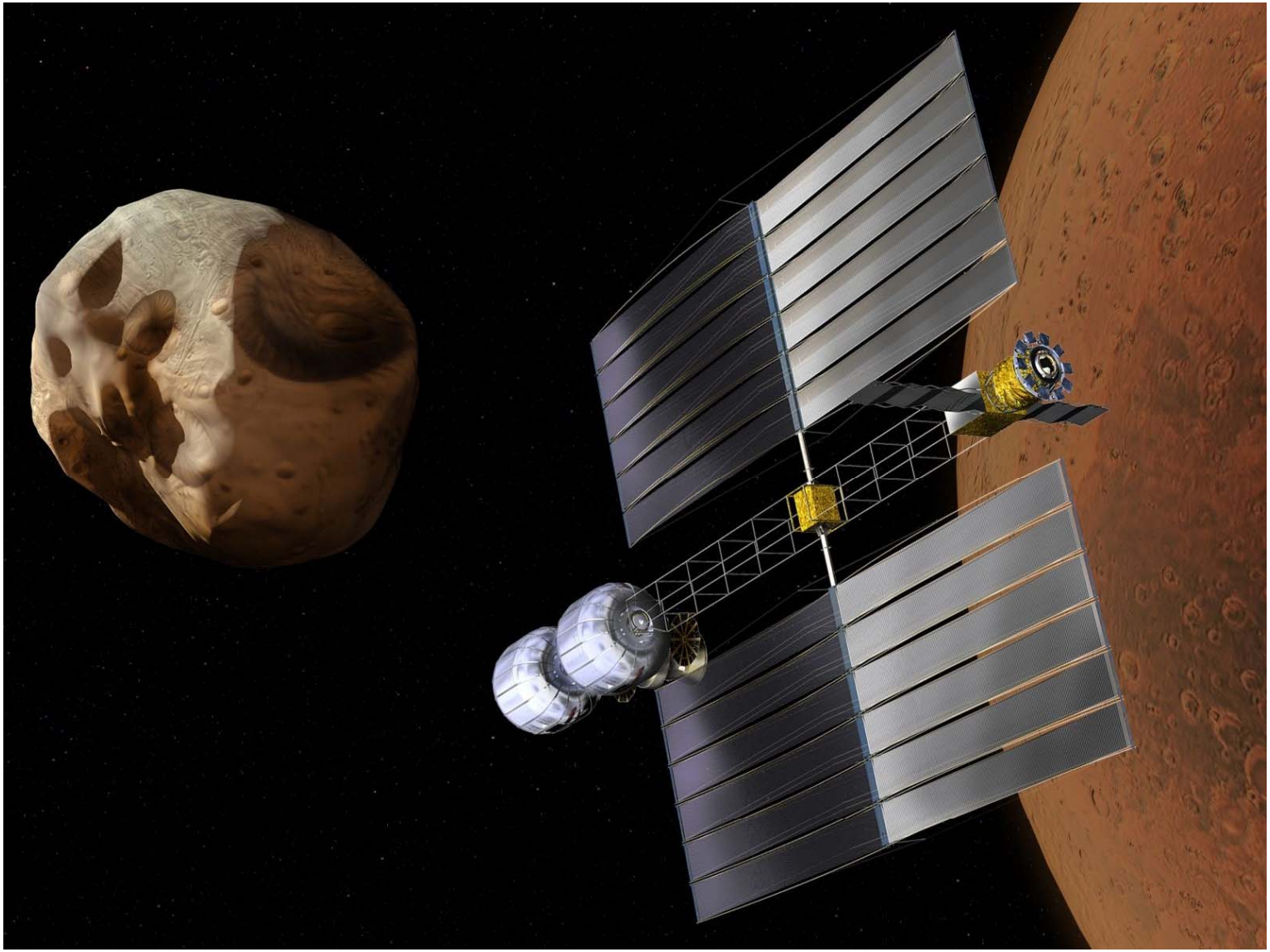
Phobos' density to too low to be solid rock, and it is known to have significant porosity. These results led to the suggestion that Phobos might contain a substantial reservoir of ice.

Mapping by the Mars Express probe and subsequent volume calcs might suggest the presence of large caverns within.

The porosity of Phobos ~30%, or nearly a third of the moon being hollow.

Copyright © 2010 Boeing. All rights reserved.

SEP at Phobos

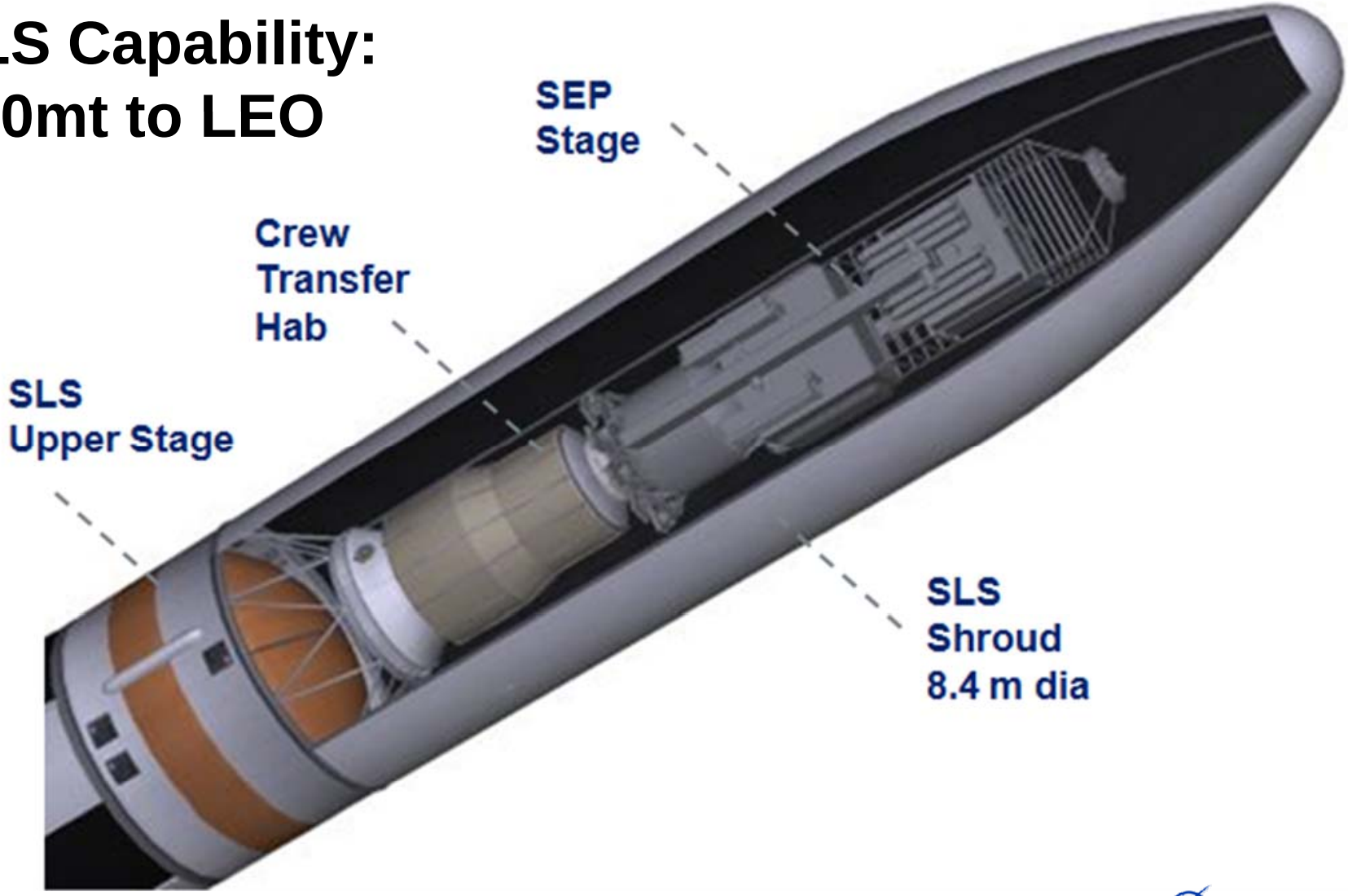


Copyright © 2010 Boeing. All rights reserved.

SLS Phobos Mission Manifest:

SEP Transfer Stage (arrays stowed) and Crew Hab (stowed)

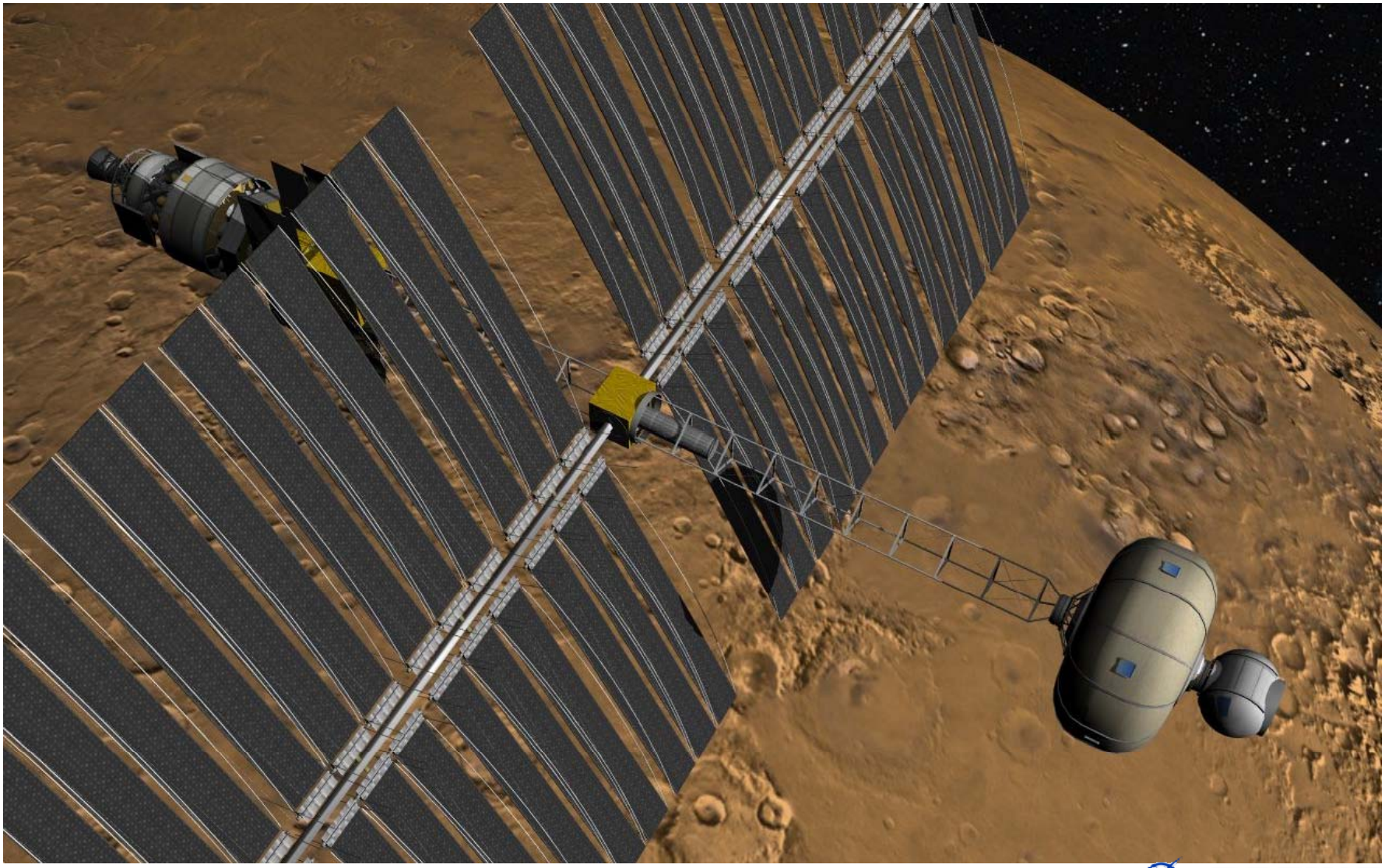
SLS Capability: 130mt to LEO



Copyright © 2010 Boeing. All rights reserved.

SEP Mars Transfer Stage

in Mars Orbit, Shown with Chemical Kick Stage



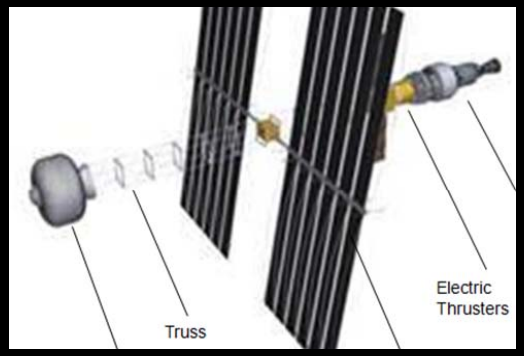
Copyright © 2010 Boeing. All rights reserved.

Mars Architecture: Major Elements

Phobos Mission

Transfer Stage

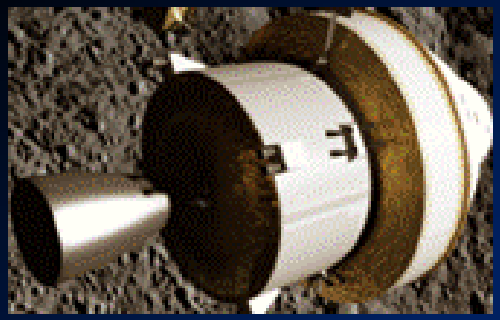
800kW Arrays



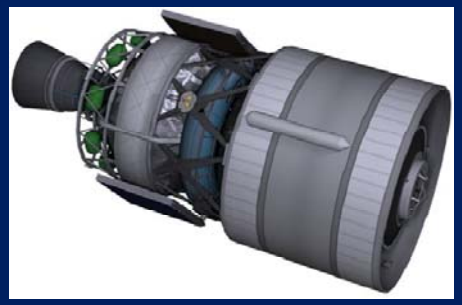
Crew Habitat

41.3 mt
Includes consumables
Avionics
Telemetry
Crew systems
ECLS

MPCV / Orion



Optional: Chem Kick Stg



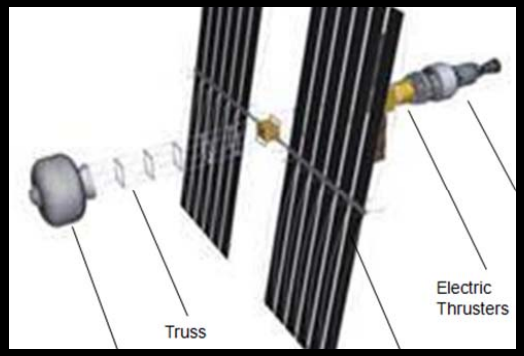
Copyright © 2010 Boeing. All rights reserved.

Mars Architecture: Major Elements

Mars Surface Mission Add Landers

Transfer Stage

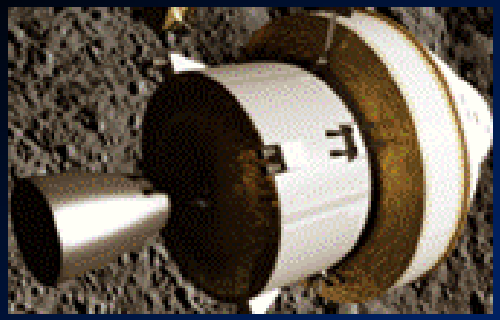
800kW-1 MW Arrays



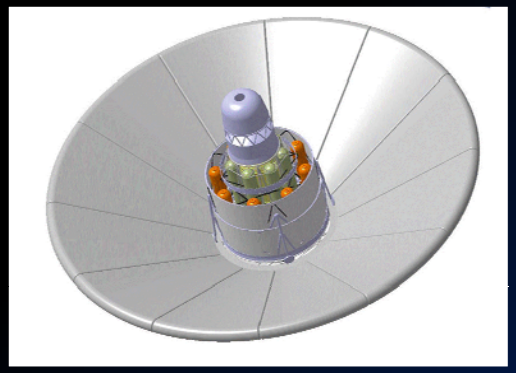
Crew Habitat

41.3 mt
Includes
consumables
Avionics
Telemetry
Crew systems
ECLS

MPCV / Orion

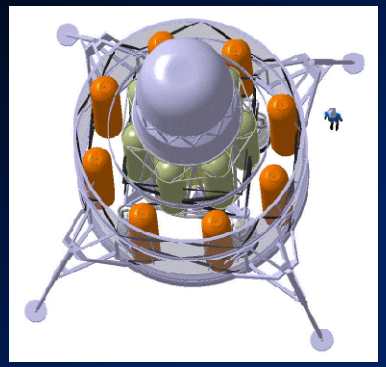


Aeroshell Lander Descent

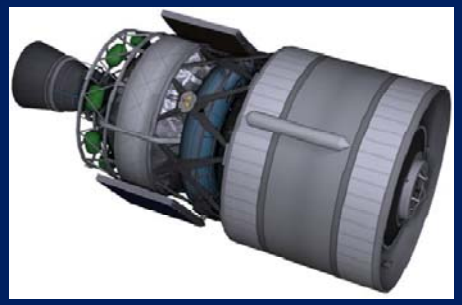


Mars Atmospheric Entry Vel <8 km/s

Mars Lander



Chem Kick Stg



Boeing All rights reserved

Step 6: Mars Surface Mission

-Crew to Surface: Phobos +Landers

Mars

Mars Surface Mission

Payloads: ***(In addition to Phobos Set)***

- **Mars Crew Lander (Ascent Stg)**
- **Mars Cargo Lander (Surface Hab)**
- **Aeroshell for Lander(s)**

Phobos

Phobos Crewed Mission (Low Mars Orbit)
Payloads: (no Lander required)
•Mars Transfer Stage + Chemical Kick Stage
•Crew Habitat (Transit: outbound and inbound)
•MPCV / Orion

NEO

NEO Crewed Mission
Payloads:
•MPCV/ Orion (x 2)
•Chemical Transfer Stage

Moon

"1 SLS per Crew Sortie" Lunar Missions
Payloads:
- MPCV / Orion
- Lander Propellant
- Lunar Surface payloads

L1
L2

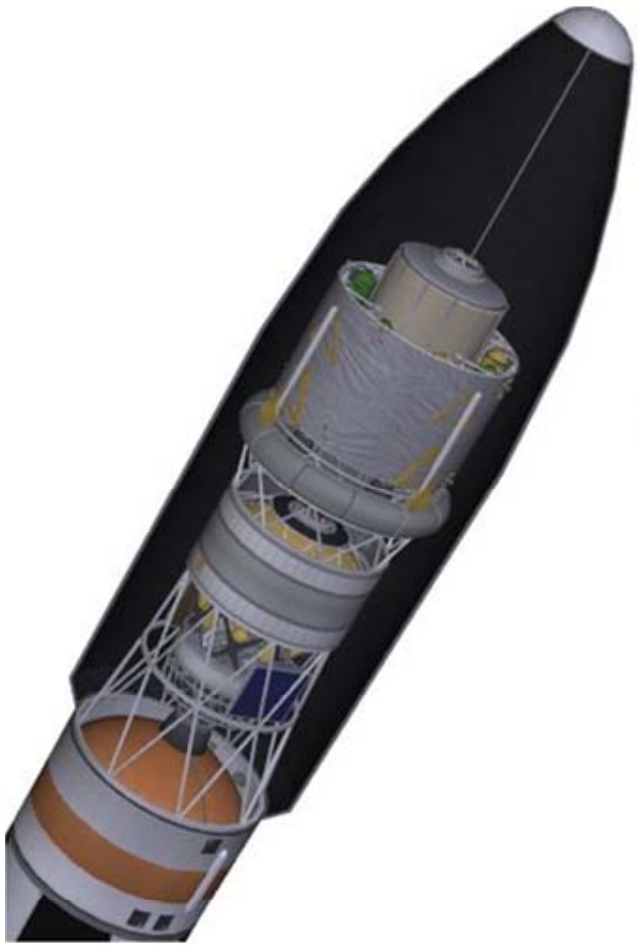
Emplace E-Moon L-Point Platform
Payloads:
- Crew Habitat
- Power Module

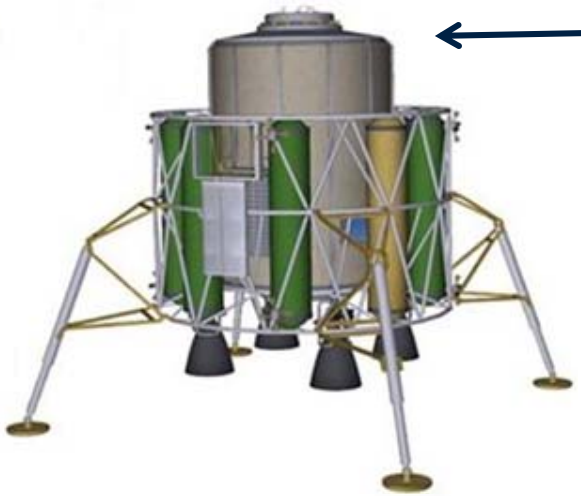
Emplace Reusable Lander
Payloads:
- MPCV/ Orion
- Reusable Lunar Lander

Copyright © 2010 Boeing. All rights reserved.

SLS Mars Cargo Lander Manifest:

8.4 meter diameter Shroud





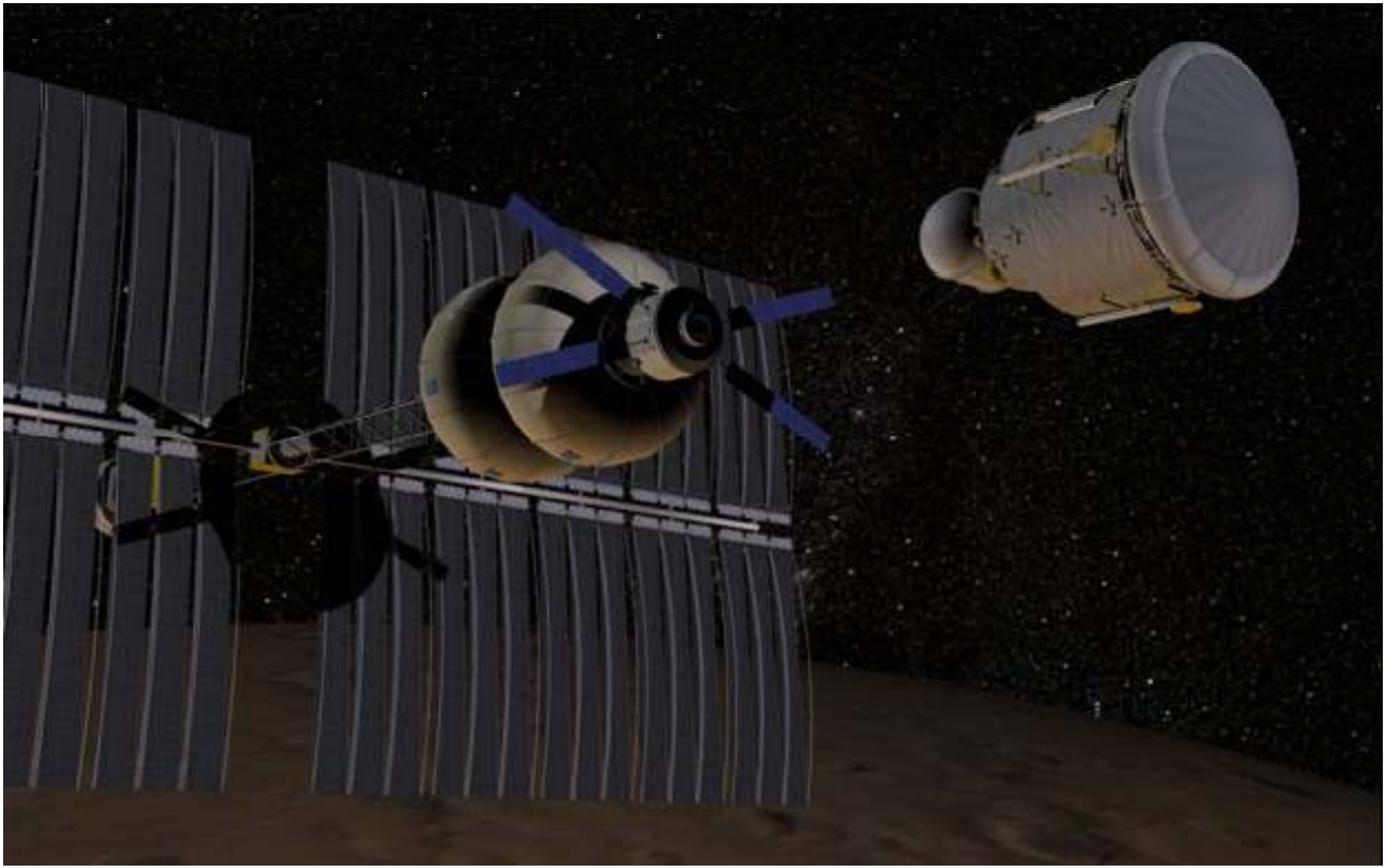
Crew Surface Habitat Cylinder (uninflated)

Crew Surface Habitat (Raised, then inflated)

Copyright © 2010 Boeing. All rights reserved.

Mars Lander Separation from MTV

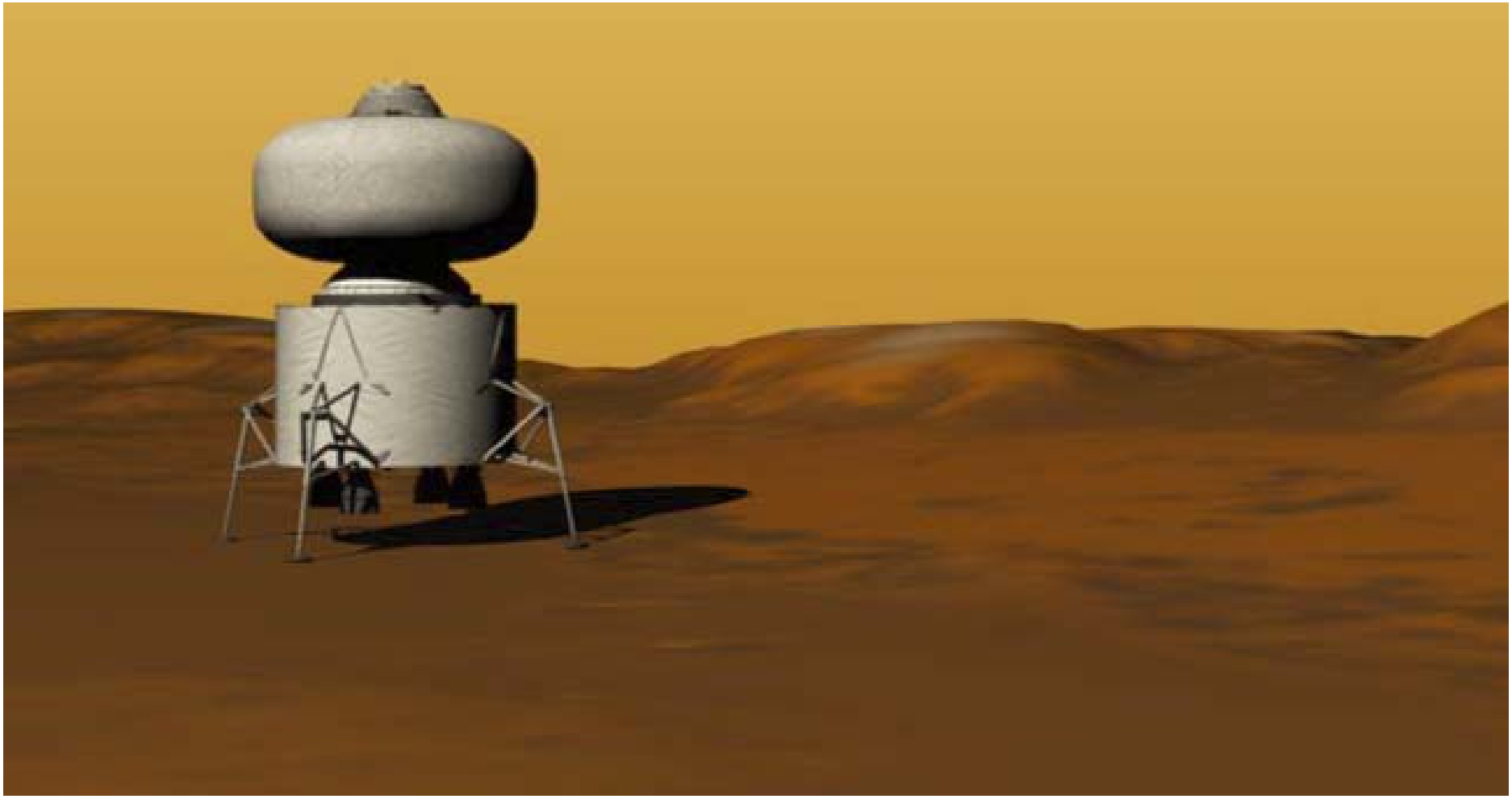
Lander Aeroshell in Stowed Configuration



Copyright © 2010 Boeing. All rights reserved.

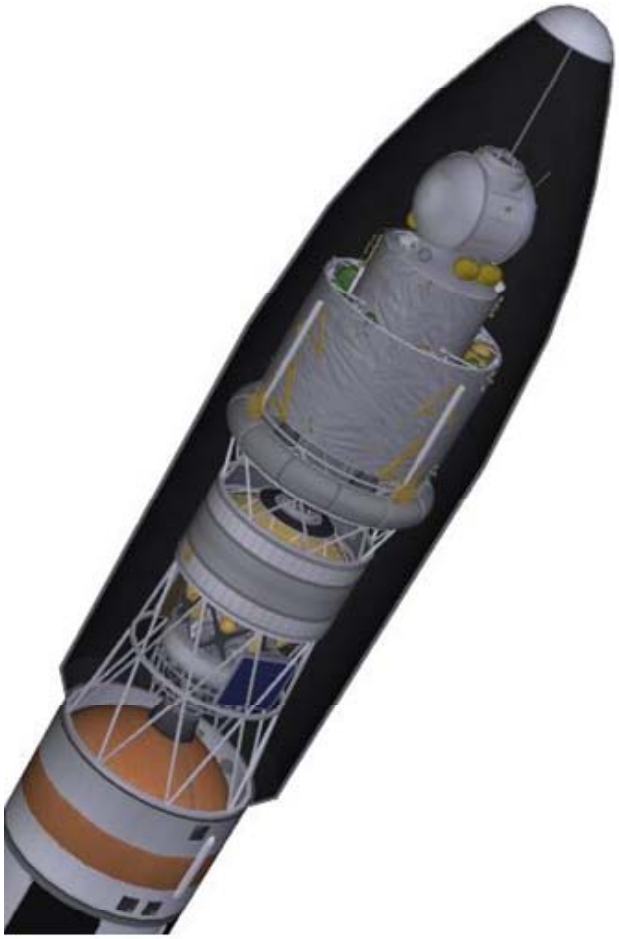
Mars Cargo Lander on Surface

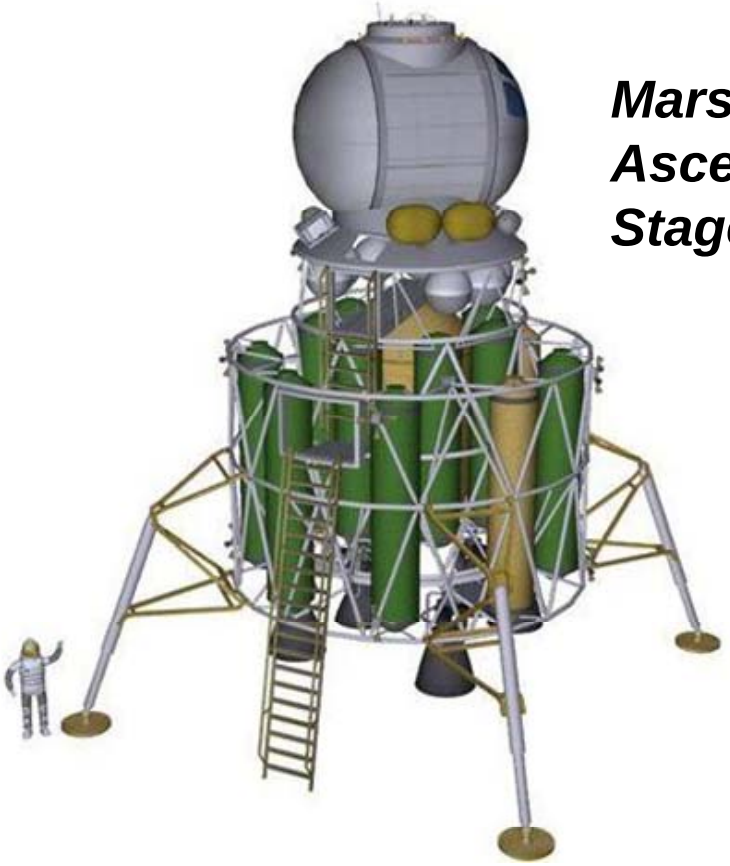
500 day Surface Mission



Copyright © 2010 Boeing. All rights reserved.

SLS Crew Lander Manifest:
in 8.4m Dia Shroud





Mars Ascent Stage

Mars Descent Stage

Copyright © 2010 Boeing. All rights reserved.

Low Thrust Mars Intercept Mission

200 day class E-M outbounds possible with <u>intercept</u> trajectories

- SEP performs Mars intercept and Flyby (1-MW SEP's capable of 200d outb)
- Crew system (hab/CRV/aeroshell) separates from SEP at Mars arrival

Crew Hab System/Aerobrake – Aerocapture at Mars

- Post aerocapture: Aeroshell is jettisoned
- Post aerocapture: circularization burn

Earth Return SEP and Mars Lander pre-emplaced in Mars orbit

- Crew system rendezvous' with Earth return SEP transfer stage
- Crew transitions to lander: descend to, and ascend from surface
- Crew returns to SEP, Ascent Stg jettison

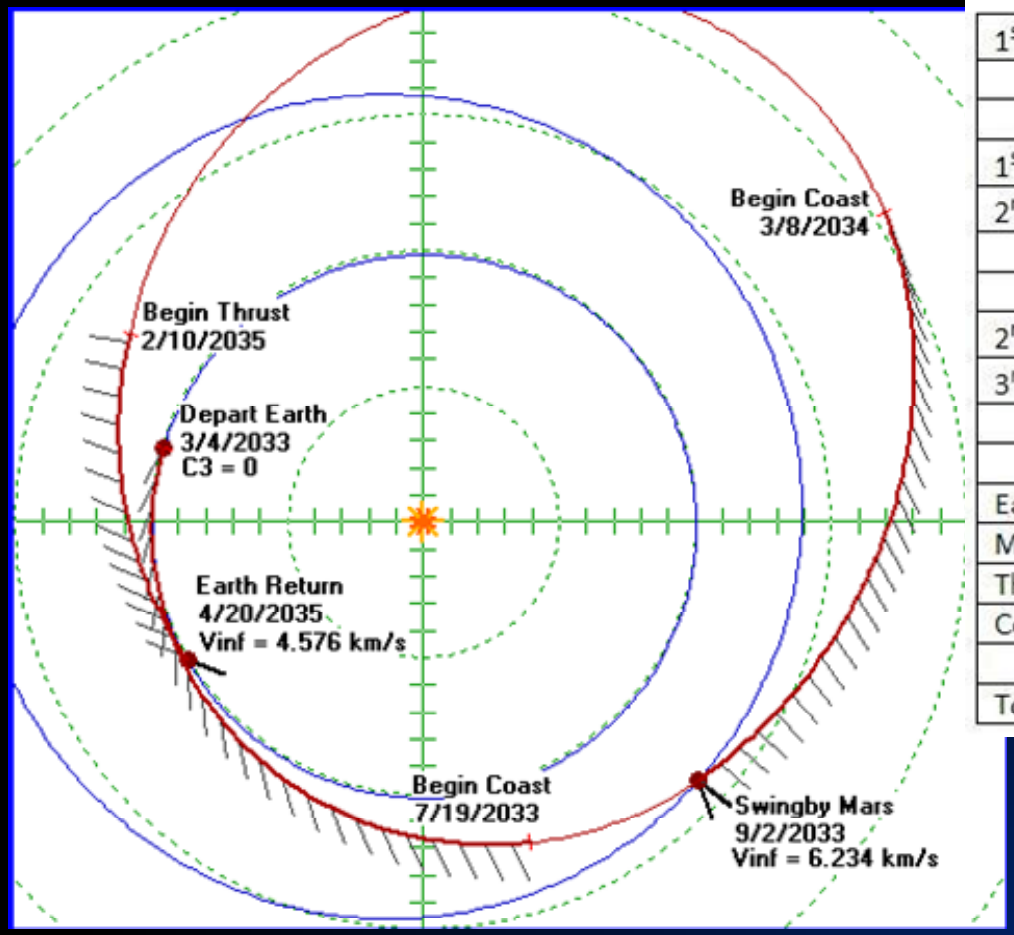
Earth Return SEP Departs Mars for Earth return

- Option: Chemical (O2/CH4) Kick stage for Mars departure
- E-Mars return trip time: function of power level, kick stage, date
- Opposition: longer return time, closer to sun, flux increase
- SEP recaptures at Earth HEO: refueled, consumables to Hab

SEP/Hab system ready for next flight

Copyright © 2010 Boeing. All rights reserved.

2033: Low Thrust Mars Flyby Profile
SEP 181 Day Outbound: Crew System Aerocapture



1st thrust period duration (days)	136.31
Δv (km/s)	4.144
1st coast period duration (days)	45.12
2nd thrust period duration (days)	187.28
Δv (km/s)	2.828
2nd coast period duration (days)	339.31
3rd thrust period duration (days)	68.98
Δv (km/s)	2.640
Earth-Mars flight time (days)	181.43
Mission duration (days)	777
Thrust time (days)	392.57
Coast time (days)	384.43
Total mission Δv (km/s)	9.611

Burn 1

Burn 2

Burn 3

Total Earth to Earth duration is 777 days
Outbound duration is 181 days
Inbound duration is 596 days

Trajectory Data provided by Jerry Horsewood of Space Flight Solutions, Inc
Using *HILTOP* low thrust trajectory optimization tool

Copyright © 2010 Boeing. All rights reserved.