Mars Design Reference Architecture 5.0 Study

Executive Summary

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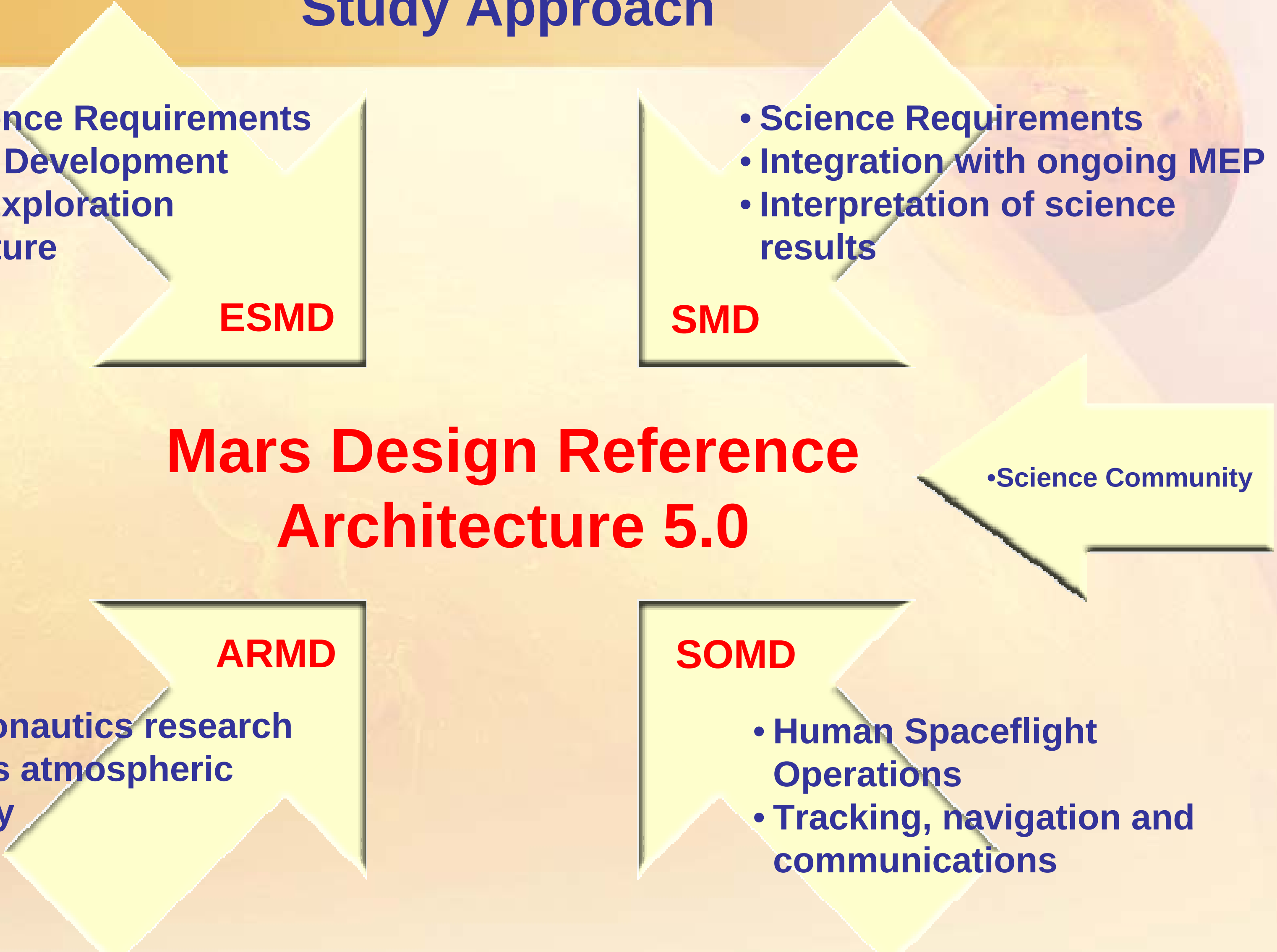
Presentation Outline

- Background of the 2007 Mars Architecture Study
- Mars Design Reference Architecture 5.0 Overview
- Decision Packages & Key Rationale
- Special Topics
  - Entry, Descent, and Landing Challenges
  - In-Space Transportation Systems
  - Launch Vehicle & Orion Assessments
  - Risk and Risk Mitigation
  - Key Driving Requirements and Challenges
  - Lunar Linkages
- Forward Work

2007 Study Objectives / Products

- Update NASA's human Mars mission reference architecture, that defines:
  - Long term goals and objectives for human exploration missions
  - Flight and surface systems for human missions and supporting infrastructure
    - Current Constellation systems and other systems updated since Mars DRM 4.0 (circa 1998)
    - Update and incorporate Mars surface reference mission into current strategy
  - An operational concept for human and robotic exploration of Mars
  - Key challenges including risk and cost drivers
  - Development schedule options (deferred)
- Assess strategic linkages between lunar and Mars strategies
- Develop an understanding of methods for reducing the cost/risk of human Mars missions through investment in research, technology development and synergy with other exploration plans, including:
  - Robotic Mars missions, Cis-lunar activities, ISS activities, Earth-based activity, including analog sites, laboratory studies, and computer simulations, additional research and technology development investment
- Develop a forward plan to resolve issues not resolved during 2007

Mars Design Reference Architecture 5.0 Study Approach



ESMD

- Non-Science Requirements
- Systems Development
- Human Exploration Architecture

SMD

- Science Requirements
- Integration with ongoing MEP
- Interpretation of science results

Mars Design Reference Architecture 5.0

- Science Community

ARMD

- Aeronautics research
- Mars atmospheric entry

SOMD

- Human Spaceflight Operations
- Tracking, navigation and communications

- Integrating all stakeholders while leveraging recognized subject matter experts
- Mission Directorates will assign and provide funding for personnel within their respective directorates

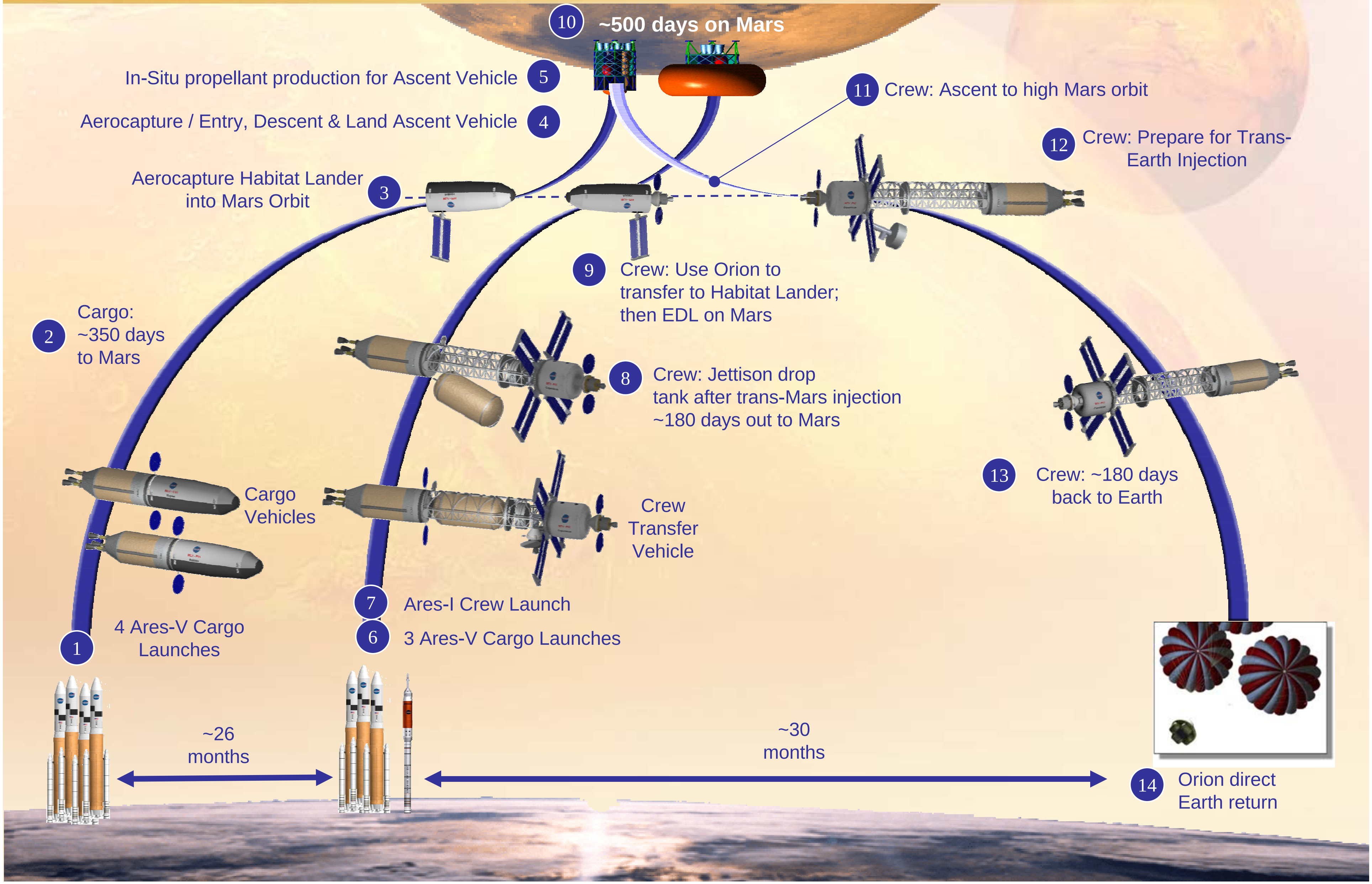
Mars Design Reference Architecture 5.0 Refinement Process

- Phase I: Top-down, High-level – Mission Design Emphasis
  - Focus on key architectural drivers and key decisions
  - Utilization of previous and current element designs, ops concepts, mission flow diagrams, and ESAS risk maturity approach information where applicable
  - Narrow architectural options (trimming the trade tree) based on risk, cost and performance
  - First order assessments to focus trade space on most promising options for Phase II
- Phase II: Strategic With Emphasis on the Surface Strategy
  - Refinement of leading architectural approach based on trimmed trade tree
  - Elimination of options which are proven to be too risky, costly, or do not meet performance goals
  - Special studies to focus on key aspects of leading options to improve fundamental approach
- Propose basic architecture decisions

Human Exploration of Mars
Key Decisions and Tenets

- Long surface stays with visits to multiple sites provides scientific diversity thus maximizing science return
- Mars systems pre-deployed to reduce mission mass and conduct system checkout prior to crew departure from Earth
- Enabling characteristics of human exploration of Mars:
  - Entry, Descent, and Landing of large payloads (40 t) – Dual use Ares V shroud
  - Robust Ares V launch campaign: 7+ launches on 30-day centers
  - Nuclear Thermal Rocket (NTR) propulsion preferred transportation option (retain chemical/aerobrake as backup)
  - ISRU : Production of ascent propellant (oxygen) and crew consumables from the atmosphere
  - Nuclear surface power : Enables In-Situ Resource Utilization (ISRU) while providing continuous robust power
  - Mobility at great distances (100’s km) from the landing site enhances science return (diversity)
  - A rich “Mars like” lunar Program which demonstrates key system behavior, operability, repair, and time on systems is necessary
  - Operation and maintenance of systems for long durations (500-1200 days) with no logistics resupply

Mars Design Reference Architecture 5.0 Mission Profile
NTR Reference Shown



⑩ ~500 days on Mars

⑤ In-Situ propellant production for Ascent Vehicle

④ Aerocapture / Entry, Descent & Land Ascent Vehicle

⑪ Crew: Ascent to high Mars orbit

⑫ Crew: Prepare for Trans-Earth Injection

③ Aerocapture Habitat Lander into Mars Orbit

⑨ Crew: Use Orion to transfer to Habitat Lander; then EDL on Mars

② Cargo: ~350 days to Mars

⑧ Crew: Jettison drop tank after trans-Mars injection ~180 days out to Mars

⑬ Crew: ~180 days back to Earth

Cargo Vehicles

Crew Transfer Vehicle

⑦ Ares-I Crew Launch

⑥ 3 Ares-V Cargo Launches

① 4 Ares-V Cargo Launches

~26 months

~30 months

⑭ Orion direct Earth return

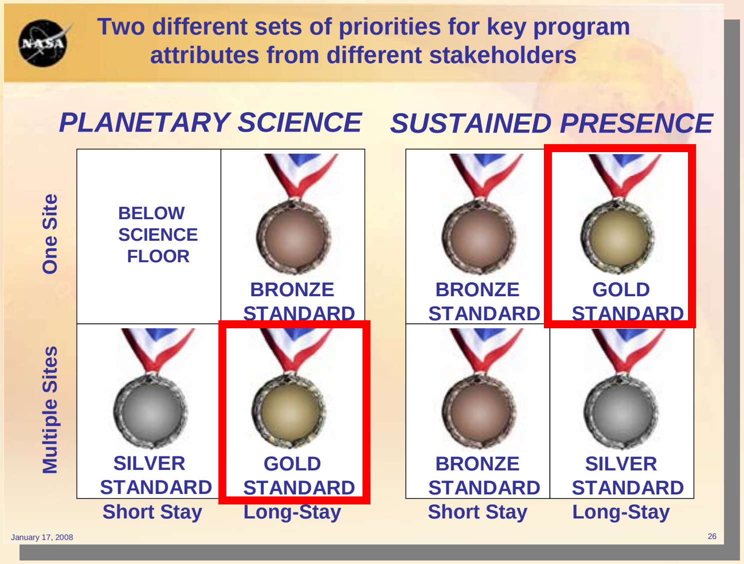
Possible Objectives
Program of First Three Human Missions

- Goals for initial human exploration of Mars organized into the following taxonomy:

Goal I	Potential for Life (MEPAG)
Goal II	Current and ancient climate (MEPAG)
Goal III	Geology & geophysics (MEPAG)

Goal IV	Preparation for human exploration (MEPAG – update pending
Goal IV+	Preparation for sustained human presence (ESMD)
Goal V	Ancillary science (SMD)

- Relationship between the resulting goals and proposed implementation approaches addressed:
  - Different exploration sites or same site?
  - Short stay (30-day) or long stay (500-days)
- Recommendation:
  - Long-stay missions overwhelmingly preferred
  - Multiple sites preferred from a science perspective
  - Same site probably better for sustained presence
  - Maximize mobility, on-Mars field (and field lab) science capability, and options for returned sample science



Two different sets of priorities for key program attributes from different stakeholders

	PLANETARY SCIENCE		SUSTAINED PRESENCE	
One Site	BELOW SCIENCE FLOOR	BRONZE STANDARD	BRONZE STANDARD	GOLD STANDARD
Multiple Sites	SILVER STANDARD	GOLD STANDARD	BRONZE STANDARD	SILVER STANDARD
	Short Stay	Long-Stay	Short Stay	Long-Stay

January 17, 2008

26

Mars Design Reference Architecture 5.0
Surface Strategy Options

- Multiple strategies developed stressing differing mixes of duration in the field, exploration range, and depth of sampling
  - Mobile Home: Emphasis on large pressurized rovers to maximize mobility range
  - Commuter: Balance of habitation and small pressurized rover for mobility and science
  - Telecommuter: Emphasis on robotic exploration enabled by teleoperation from a local habitat

DRA 5.0 Reference

- Mobility including exploration at great distances from landing site, as well as sub-surface access, are key to Science Community
- In-Situ Consumable Production of life support and EVA consumables coupled with nuclear surface power provides greatest exploration leverage
- Development of systems which have high reliability with minimal human interaction is key to mission success

Design Reference Architecure 5.0 Summary

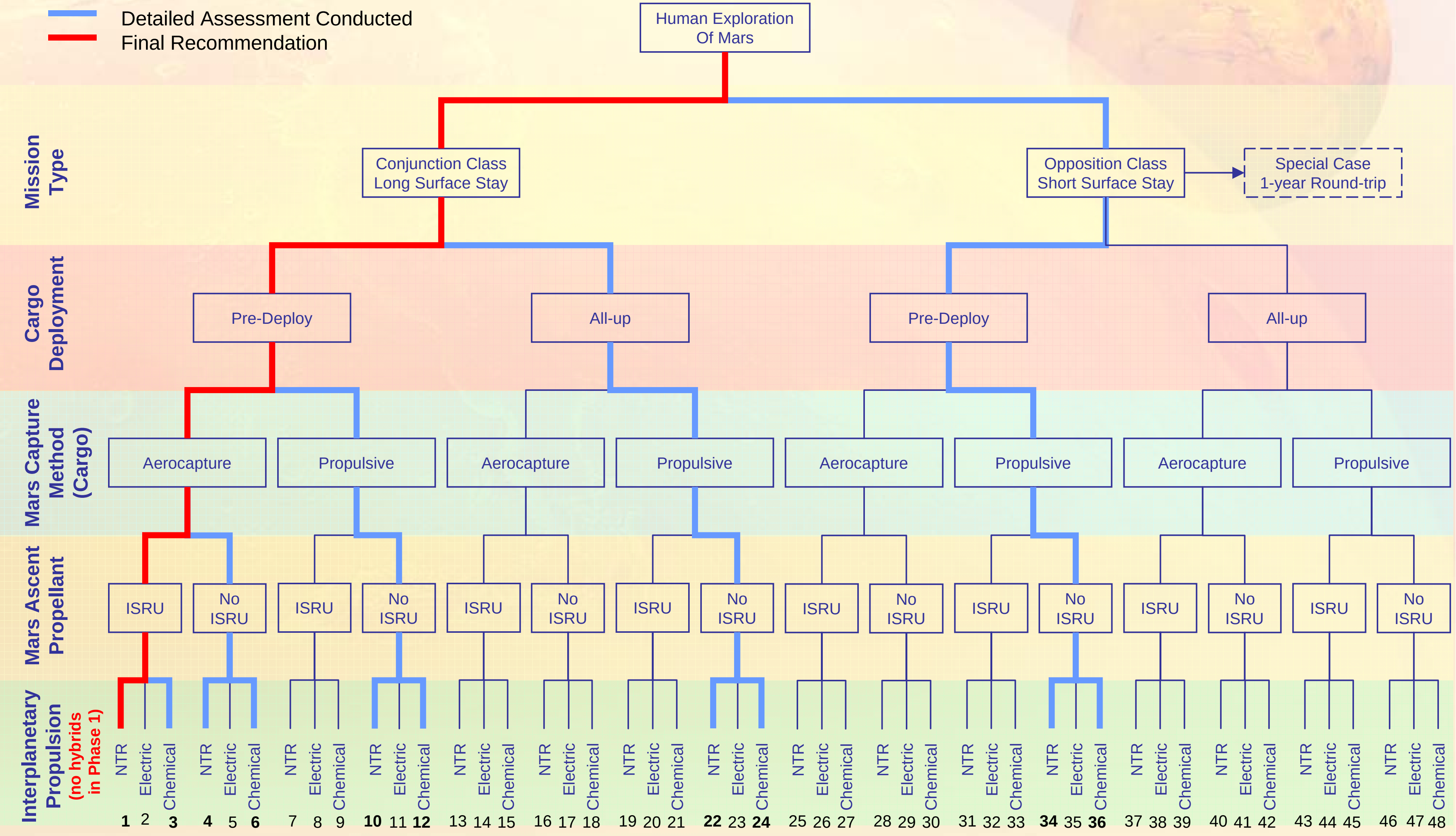
	NTR Reference	Chemical Option
Total Crew Flight Duration (approx. days) *	**~900**	**~900**
Crew Transit time LEO-Mars (approx. days)	**~180**	**~180**
Crew Mars Stay Time (approx. days)	**~540**	**~540**
Crew Transit time Mars-Earth (approx. days)	**~180**	**~180**
Total Initial MTV Mass in LEO (IMLEO) (t) **	**825**	**1252**
Crew Vehicle Mass	**333**	**534**
Inter-Planetary Transportation (t)	282	483
Crew Transit Payload (t)	51	51
Cargo Vehicle Mass (mt each)	**246**	**359**
Inter-Planetary Transportation (t)	144	257
Mars Surface Payload (t)	36	36
Propulsive Lander (wet, t)	23	23
Aeroshell Mass (t)	43	43
Launch Data †		
Ares-I Launches (crew)	**1**	**1**
Ares-V Launches (cargo)	**7-9**	**10-12**
Launch Campaign Duration (days)	**300**	**390**

* Trip times are average durations across the synodic cycle
** All mass data exclusive of Project and Program reserves
† Number of launches dependent on launch vehicle selected

Mars Design Reference 5.0

Decision Packages

Mars Design Reference Architecture 5.0
Top-level Trade Tree



🟦 Detailed Assessment Conducted
🟥 Final Recommendation

Mission Type | Cargo Deployment | Mars Capture Method (Cargo) | Mars Ascent Propellant | Interplanetary Propulsion (no hybrids in Phase 1)

- Human Exploration Of Mars
  - Conjunction Class Long Surface Stay
    - Pre-Deploy
      - Aerocapture
        - ISRU: NTR **1**, Electric 2, Chemical **3**
        - No ISRU: NTR **4**, Electric 5, Chemical **6**
      - Propulsive
        - ISRU: NTR 7, Electric 8, Chemical 9
        - No ISRU: NTR **10**, Electric 11, Chemical **12**
    - All-up
      - Aerocapture
        - ISRU: NTR 13, Electric 14, Chemical 15
        - No ISRU: NTR 16, Electric 17, Chemical 18
      - Propulsive
        - ISRU: NTR 19, Electric 20, Chemical 21
        - No ISRU: NTR **22**, Electric 23, Chemical **24**
  - Opposition Class Short Surface Stay → Special Case 1-year Round-trip
    - Pre-Deploy
      - Aerocapture
        - ISRU: NTR 25, Electric 26, Chemical 27
        - No ISRU: NTR 28, Electric 29, Chemical 30
      - Propulsive
        - ISRU: NTR 31, Electric 32, Chemical 33
        - No ISRU: NTR **34**, Electric 35, Chemical **36**
    - All-up
      - Aerocapture
        - ISRU: NTR 37, Electric 38, Chemical 39
        - No ISRU: NTR 40, Electric 41, Chemical 42
      - Propulsive
        - ISRU: NTR 43, Electric 44, Chemical 45
        - No ISRU: NTR 46, Electric 47, Chemical 48

NTR- Nuclear Thermal Rocket
Electric= Solar or Nuclear Electric Propulsion

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2007 Key Decision Packages – Mission Type

Question	Which mission type, conjunction class (long surface stay) or opposition class (short surface stay) provides the best balance of cost, risk, and performance?
Recommendation	**Conjunction class (Long-stay) missions**
Notable Advantages of Conjunction Class (Long-Stay) Missions	• Best exploration value for cost • Ample time for crew acclimation and planetary operations/contingencies and surface exploration • Zero-g transits (~180 days) within our current experience base. Lunar Outpost will provide vital hypo-gravity data for human performance associated with long surface stays for feed forward to Mars • Less total radiation exposure (as known today – surface radiation environment characterization needed). No other significant human performance factors identified. • No close perihelion passage reduces radiation and thermal risks • Lower total delta-v and less variation in delta-v across the synodic cycle • Less sensitive to changes in propulsive delta-v and thus less architectural sensitivity • Provides ability to maintain similar vehicle size for both crew and cargo vehicles • Orion Earth return speed "within Orion family" – 12 km/s (TPS implications)
Notable Disadvantages	• Longer total mission duration • Slightly higher overall total mission cost (assuming opposition class missions do not require dedicated surface habitats

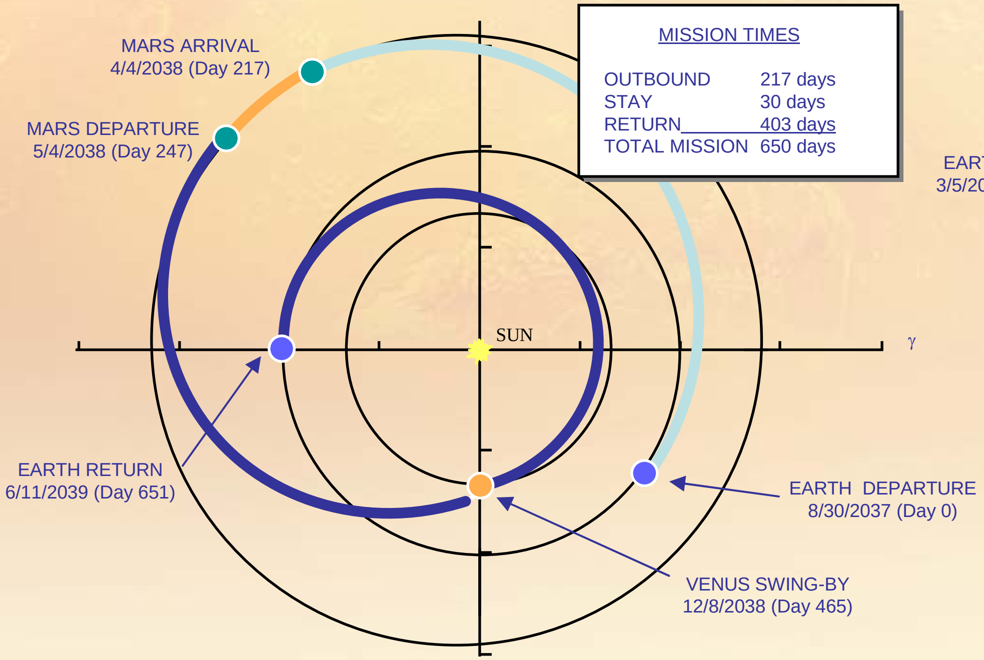
Mars Design Reference Architecture 5.0
Mars Trajectory Classes

Short-Stay Missions

- Variations of missions with short Mars surface stays and may include Venus swing-by
- Often referred to as Opposition Class missions

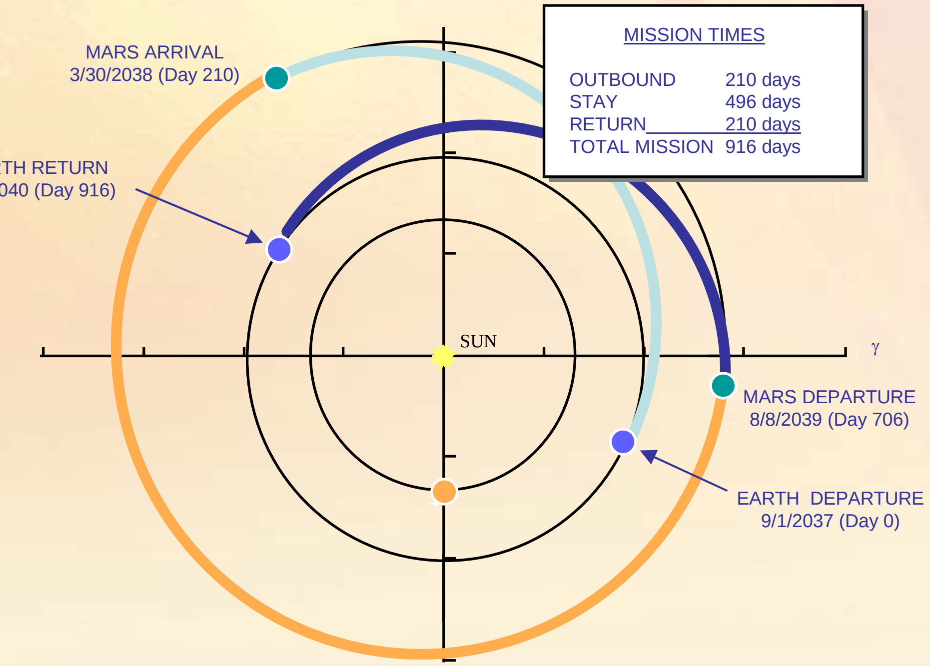
Long-Stay Missions

- Variations about the minimum energy mission
- Often referred to as Conjunction Class missions



MISSION TIMES

OUTBOUND	217 days
STAY	30 days
RETURN	403 days
TOTAL MISSION	650 days



MISSION TIMES

OUTBOUND	210 days
STAY	496 days
RETURN	210 days
TOTAL MISSION	916 days

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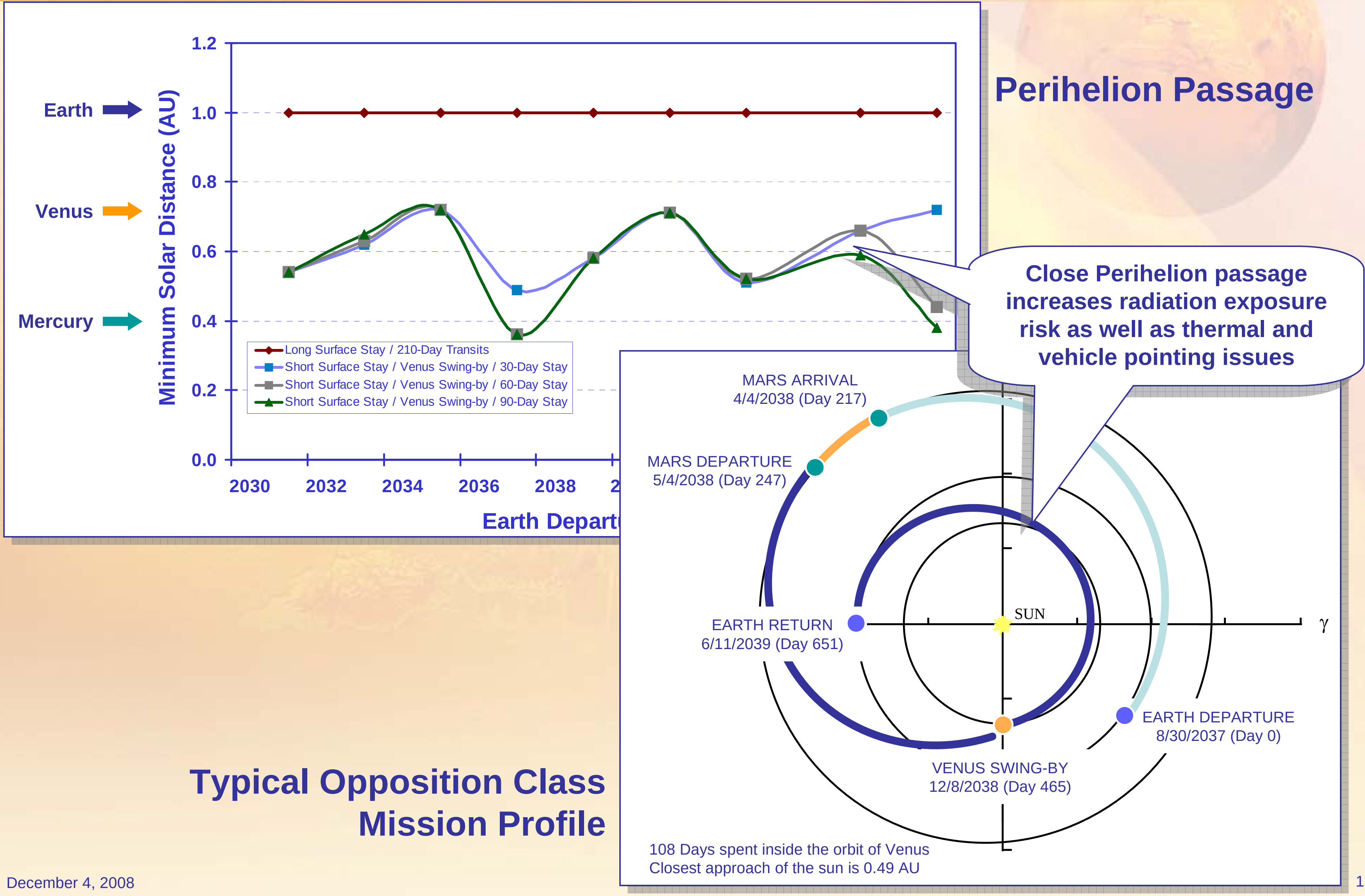
Mission Type Close Perihelion Passage

Perihelion Passage



Close Perihelion passage increases radiation exposure risk as well as thermal and vehicle pointing issues

108 Days spent inside the orbit of Venus
Closest approach of the sun is 0.49 AU

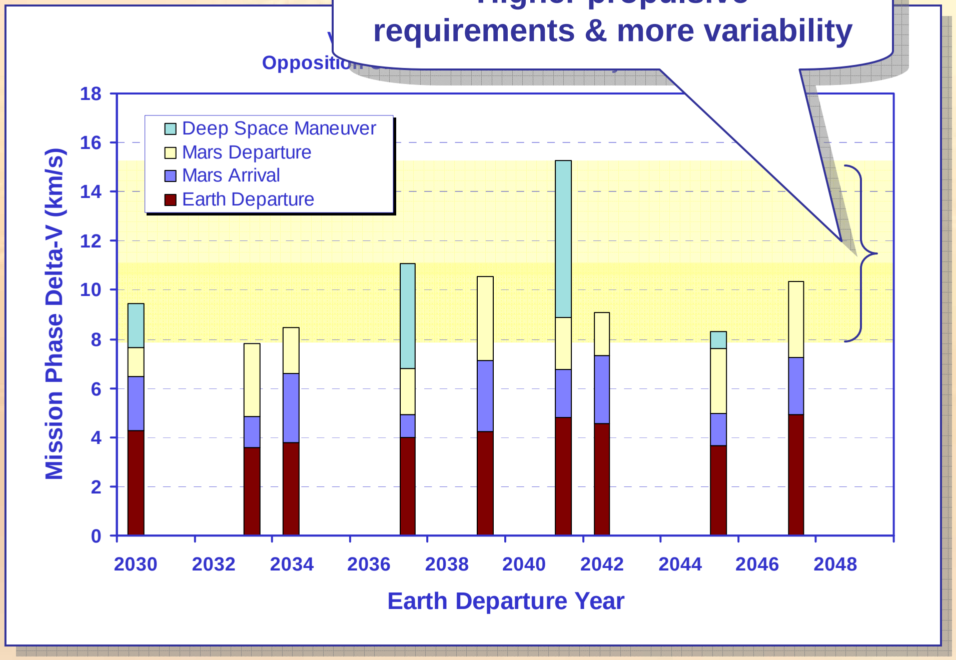
Typical Opposition Class Mission Profile

Mars Design Reference Architecture 5.0
Total Interplanetary Propulsion Requirements

Opposition Class Missions

(Short-Stay)

Propulsive Delta-V



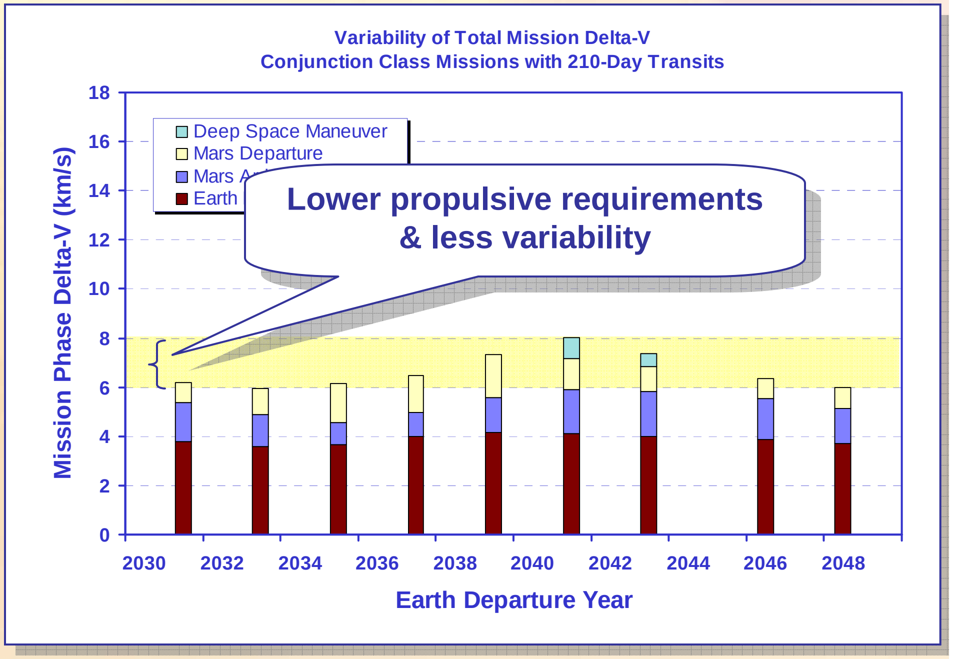
Higher propulsive requirements & more variability

Note: Optimized trajectories assuming 407 km circular LEO departure orbit, propulsive capture at Mars into a Mars 1-Sol orbit of 250 km x 33,793 km. 30 sols stat at Mars. Direct entry at Earth with an entry speed limit of 13 km/s.

Conjunction Class Mission

(Long-Stay)

Propulsive Delta-V



Lower propulsive requirements & less variability

Note: Optimized trajectories assuming 407 km circular LEO departure orbit, propulsive capture at Mars into a Mars 1-Sol orbit of 250 km x 33,793 km. 210 day transits to and from Mars. Direct entry at Earth with an entry speed limit of 13 km/s.

Mars Design Reference Architecture 5.0
Mission Type Total Mission Duration

Opposition Class Missions

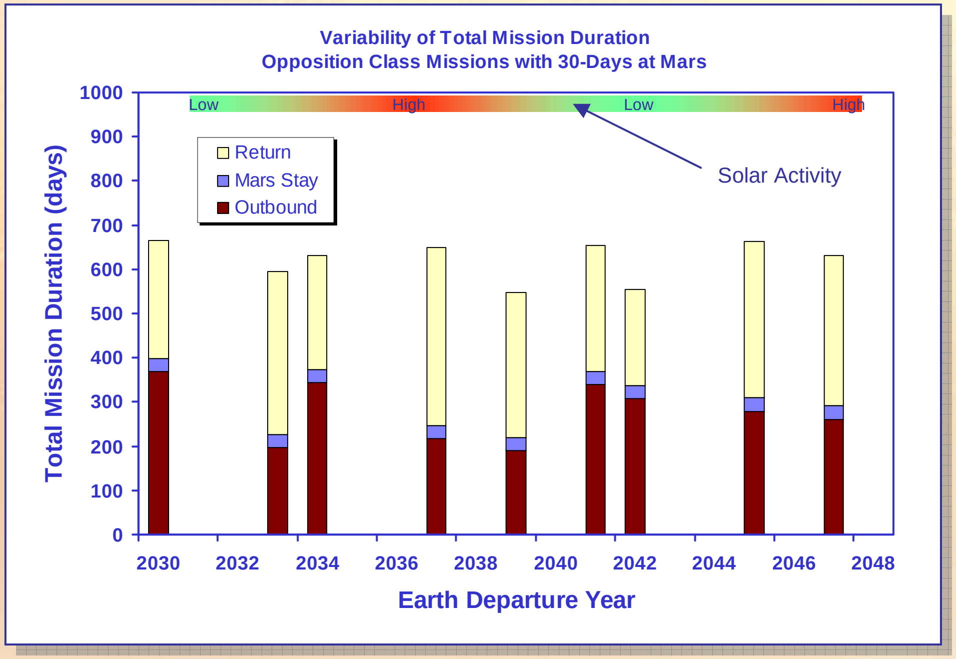
(Short-Stay)

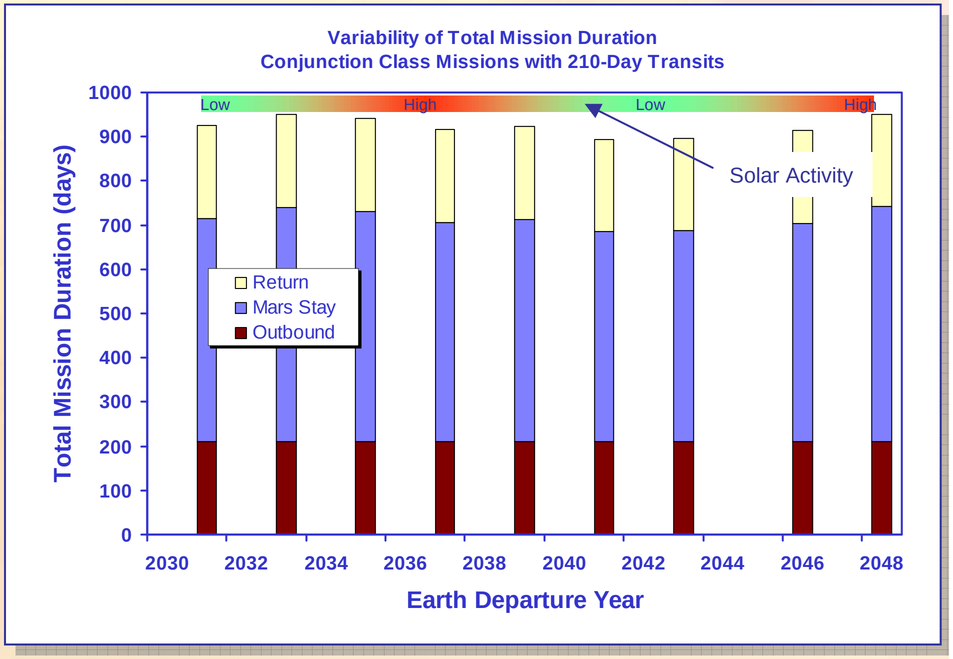
Total Mission Duration

Conjunction Class Mission

(Long-Stay)

Total Mission Duration


Variability of Total Mission Duration
Opposition Class Missions with 30-Days at Mars


Variability of Total Mission Duration
Conjunction Class Missions with 210-Day Transits

% of time at Mars: ~5%

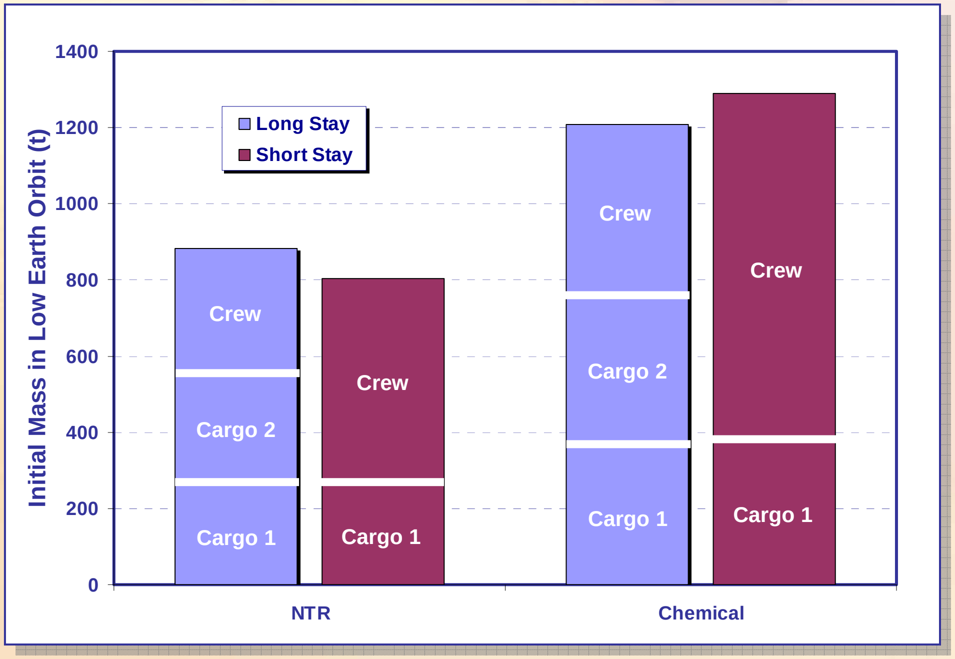
% of time at Mars: ~55%

- **Advantage: Long-Stay – maximizes exploration return**

Mars Design Reference Architecture 5.0
Mission Type Total Mass Comparison

- Total mission mass essentially the same when “hardest” short-stay opportunity not considered.
- Short-stay missions may require fewer elements (inclusion of surface habitat lander dependent on length of stay), but require more interplanetary propulsion (3-7 km/s extra)
- Long-stay mission utilizes more energy efficient trajectories, but requires more mission elements:
  - Surface Habitat Lander
  - Surface exploration systems

Total Mission Mass

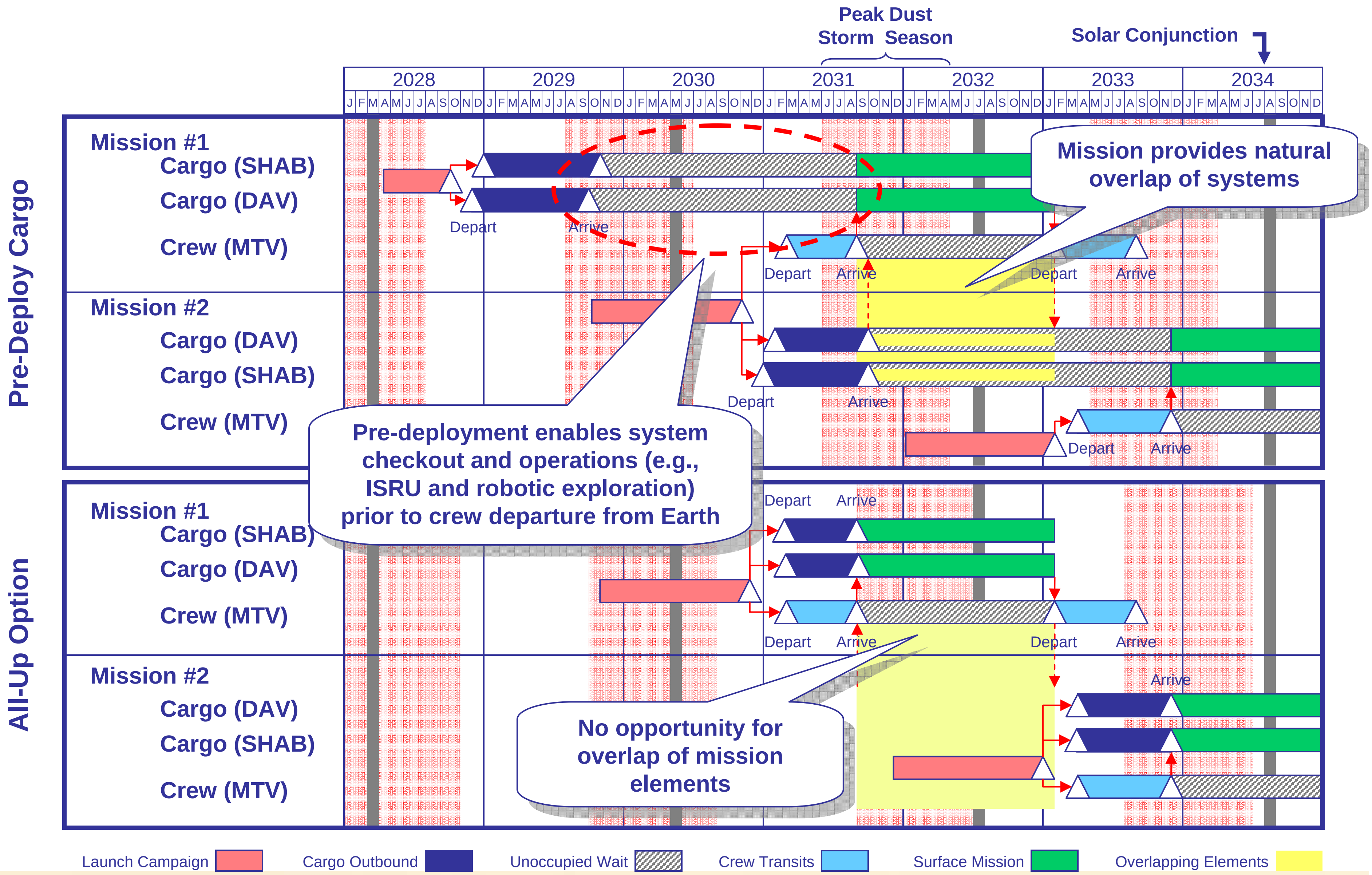


- Advantage: Long-Stay. Enables common vehicle design for both crew and cargo missions

Mars Design Reference Architecture 5.0
2007 Key Decision Packages – Cargo Deployment

Question	Should mission assets, which are not used by the crew until arrival at Mars, be pre-deployed ahead of the crew?
Recommendation	**Pre-deploy cargo one opportunity ahead of the crew**
Other Questions	• Is a lifeboat mode (e.g. Apollo 13) feasible/advantageous for human Mars missions? • What are the architectural advantages of all-up versus pre-deploy mission modes?
Notable Advantages of Pre-Deployment	• Enables strategies such as In-situ Resource Utilization • Mission design provides natural functional redundancy to reduce crew risk • Verification of cargo arrival at Mars and operational condition prior to crew departure from Earth • Satisfies more exploration goals via robotic exploration prior to crew arrival • Lower total initial mass in Low-Earth Orbit • Reduces outbound vehicle size and complexity
Notable Disadvantages	• Longer cumulative time on systems • Slightly higher costs (mission operations time)

Long and Short Mission Sequences
Pre-Deploy Option



Mission provides natural overlap of systems

Pre-deployment enables system checkout and operations (e.g., ISRU and robotic exploration) prior to crew departure from Earth

No opportunity for overlap of mission elements

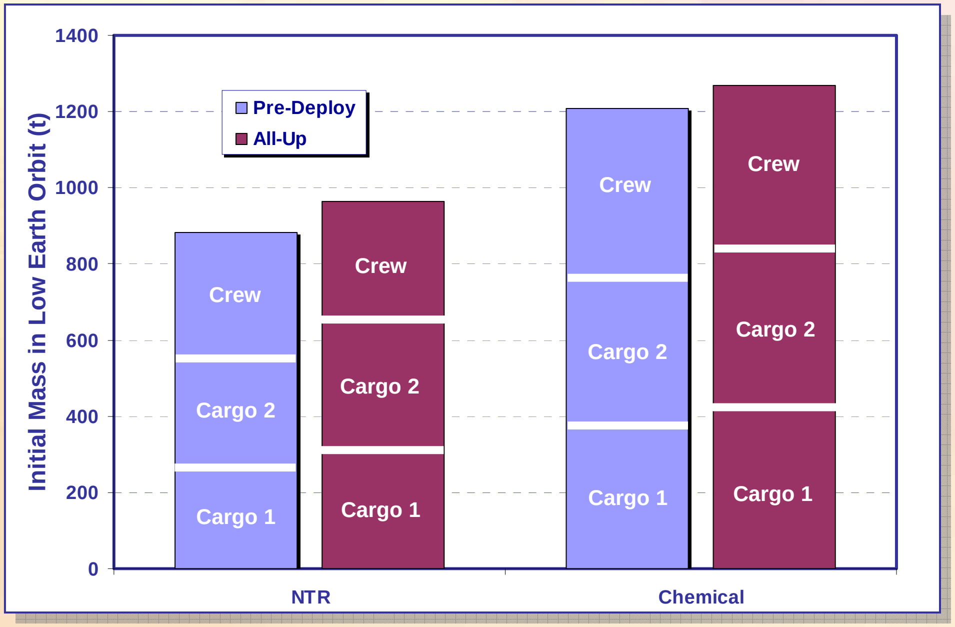
Mars Design Reference Architecture 5.0
Pre-Deploy Cargo vs. All-Up Mass Comparison

- **Advantage: Pre-Deploy Option (but not significantly better)**
  - **Total mission mass consistently higher for the all-up option since all vehicles fly faster "crew" trajectories**
  - **Sending Mars cargo on slower minimum-energy trajectories reduces mission mass for the pre-deploy option**
  - **All-up integrated vehicle approach is challenging**
    - Requires assembly of all large vehicle elements in LEO prior to departure

    or

    - Hyperbolic rendezvous while in transit to Mars

Total Mission Mass



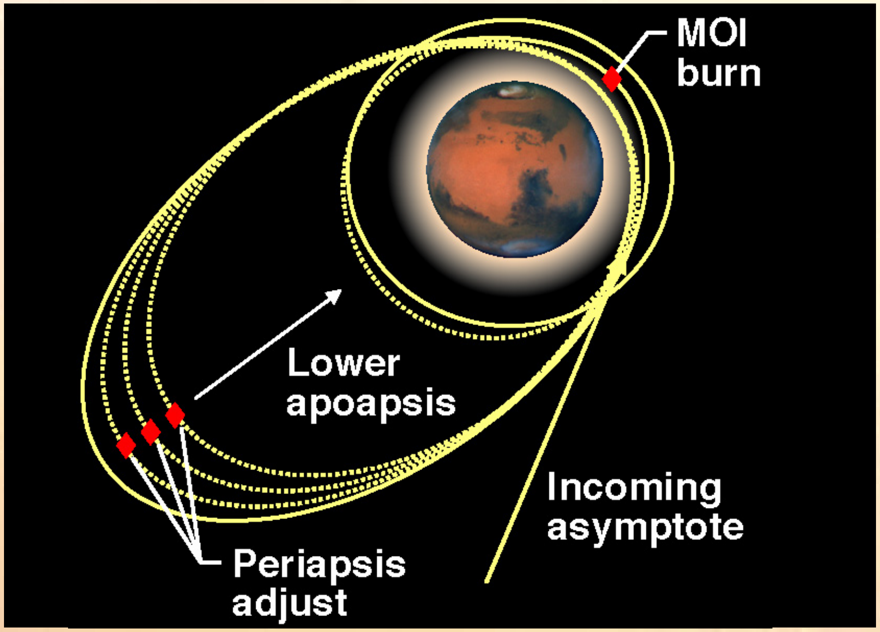
Mars Design Reference Architecture 5.0
2007 Key Decision Packages – Mars Orbit Capture

Question	Should the atmosphere of Mars be used to capture mission assets into orbit (aerocapture) or propulsive capture?
Recommendation	**Retain aerocapture for Mars cargo elements**
Notes	• Benefit of aerocapture is dependent on the interplanetary propulsion used (If NTR is used, the issue becomes one of risk. If chemical is used, aerocapture was considered enabling) • Aerocapture for the crew transfer vehicle was eliminated from consideration due to the physical size of that element
Notable Advantages of using Aerocapture for Mars Orbit Insertion	• Aerocapture reduces total architecture mass • Less architecture sensitivity to changes in payload mass • Minimal thermal protection system impacts. Both heat rate (factor of 3) and heat load (factor of 2) are less than those that will be experienced for Orion Earth return • Aerocapture guidance techniques are subsets of Orion skip trajectories
Notable Disadvantages	• Dual use of TPS (aerocapture followed by EDL) increases overall risk • Heat rejection and thermal load on primary structure yet to be assessed and will add mass and complexity

Entry, Descent, and Landing large payloads on the surface of Mars remains a critical challenge for human exploration of Mars

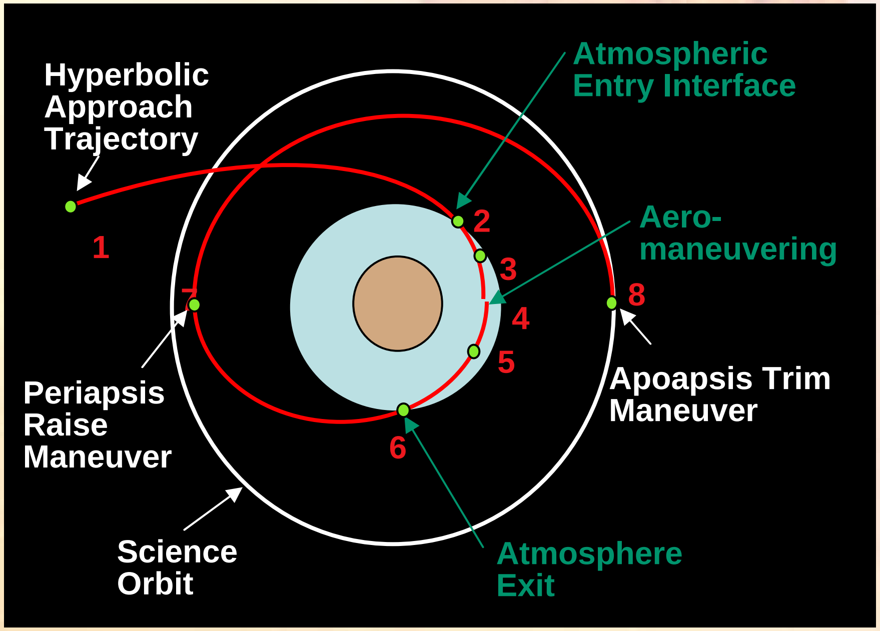
Aeroassist Reference Terminology

Aerobraking



- Mature approach: Magellan-1993 experiment at Venus. Used on last 3 Mars Orbiters (MGS-1996, Odyssey-2001, MRO-2005).
- Spacecraft performs multiple atmospheric passes, in very thin upper atmosphere, which lowers apoapsis on successive orbits
- Labor intensive operations, typically lasting 4-6 months
- May or may not require special adaptations (e.g. TPS, aeroshell, drag devices) depending on the depth, number and duration of the aerobraking mission phase
- Not considered a viable option for Mars Orbit Insertion

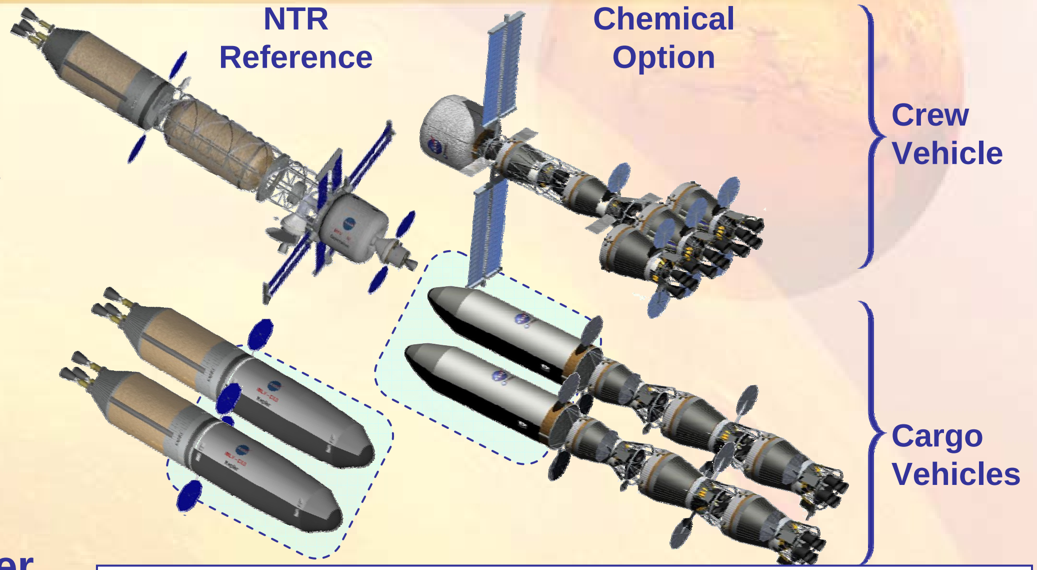
Aerocapture

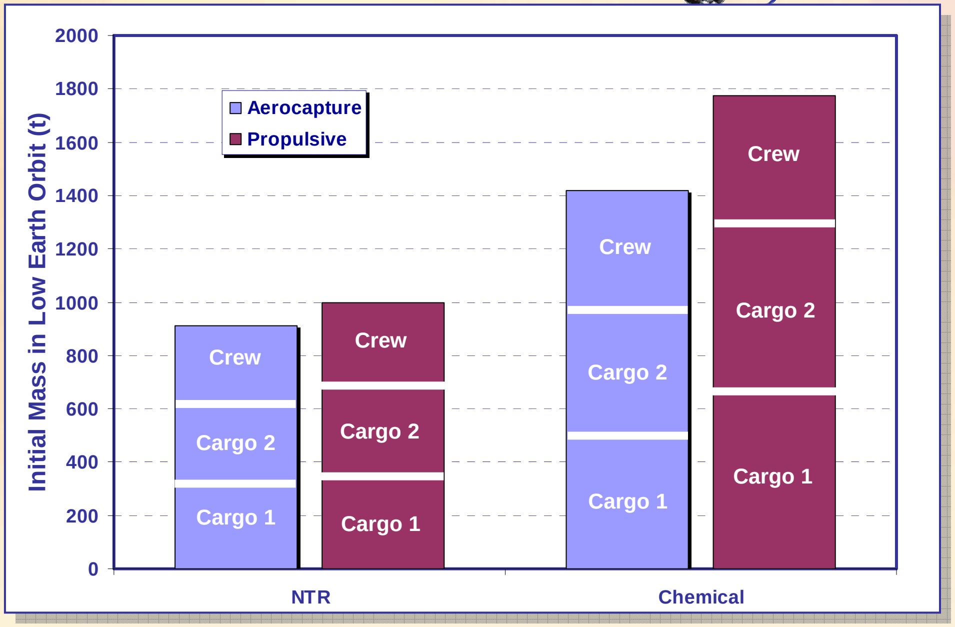


- Direct capture into Mars orbit from arrival trajectory using single, atmospheric aerodynamic drag pass
- Requires an aeroshell with TPS, and an atmospheric flight guidance and control algorithm
- This technique not yet demonstrated on an operational mission
- TPS challenges are thought to be no more demanding than direct entry TPS (but are configuration specific to new shapes)
- Guidance requirements are similar to those for a skip reentry maneuver (used for CEV/Orion lunar return & MSL)

Mars Design Reference Architecture 5.0
Aerocapture versus Propulsive Capture Mass Comparison

- **Advantage: Aerocapture**
  - Total mission mass consistently higher for all-propulsive option
  - Aerocapture savings are dependent on the in-space transportation system used
  - Significant aerocapture savings for chemical transportation system (aerocapture is an enabler for the chemical propulsion option)
  - Further assessments of aerocapture and EDL options are required
  - Note: Aerocapture for the crew transfer vehicle was eliminated from consideration due to the physical size of that element

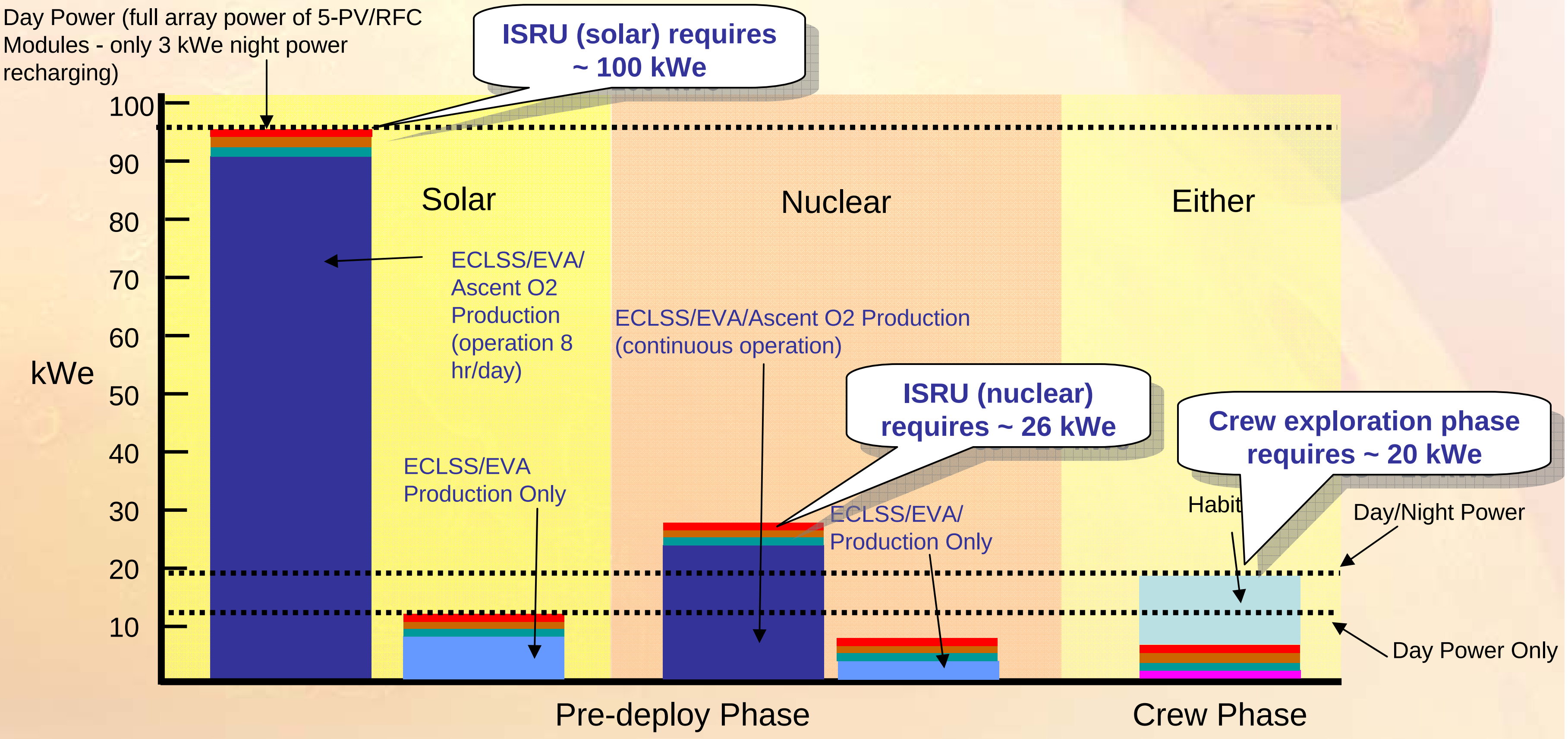




Mars Design Reference Architecture 5.0
2007 Key Decision Packages – ISRU

Question	Should locally produced propellants be used for Mars ascent?
Recommendation	**ISRU is enabling for robust human Mars missions**
Notable Advantages of In-Situ Resource Utilization	• Production of oxygen from the atmosphere for ascent from Mars as well as consumables (oxygen, buffer gases, water) for the crew enables robust exploration • Atmospheric based ISRU processes less operationally complex than surface based • Reduced total initial mass in Low-Earth Orbit and subsequent number of launches • Reduced lander vehicle size and volume • Greater surface exploration capability (EVA, roving, etc.) • Life support functional redundancy via dissimilar means • Lower mission risk due to fewer launches • Lower life cycle cost through third mission (if same landing site)
Notable Disadvantages	• Requires slightly more peak power • Longer cumulative time on systems • Rendezvous with surface ascent vehicle required for crew return to orbit (see note).
Notes	• Abort to orbit during EDL deemed not feasible. Thus, for human exploration of Mars emphasis should be placed on abort to surface and landing accuracy.

Mars Design Reference Architecture 5.0
Power Requirement Estimate



🟥 Rover Recharge
🟧 Logistics Module
🟦 Ascent Stage
🟪 ECLSS/EVA Cache

Legend

Deliver 5 - 5 kWe PV/RFC Modules
*** Sufficient for O2 production when Habitat in standby Mode**
*** Not capable of dust storm crew survival**

Mars Design Reference Architecture 5.0
Lander Size Comparison for ISRU

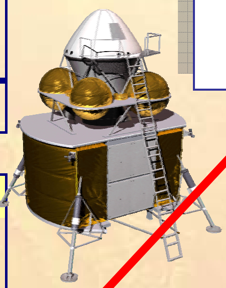
Mars Ascent Vehicle Trade

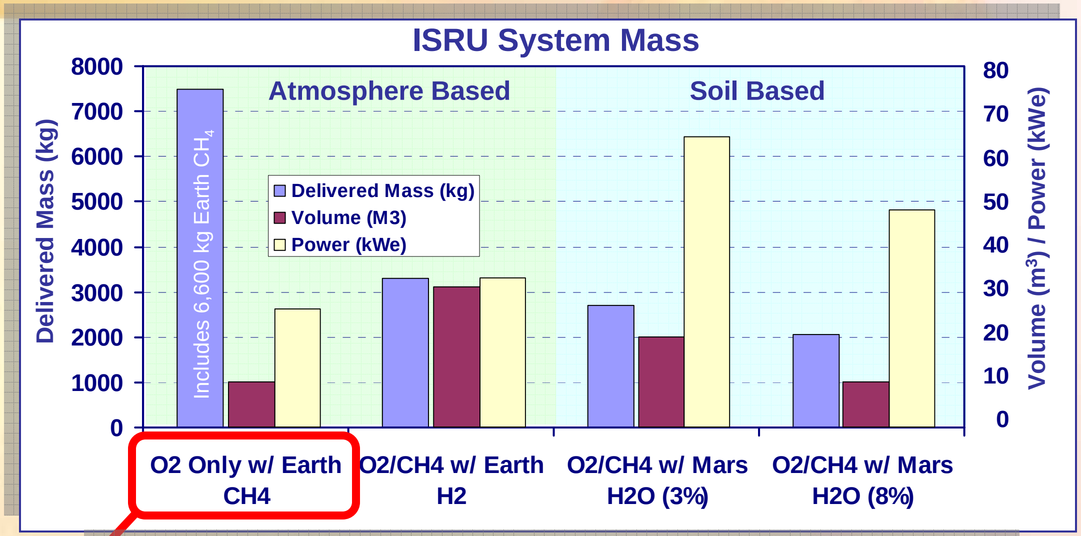
- Assumes ascent to a 1-sol orbit
- LO_2/LCH_4 pump-fed propulsion
- Large delta-V margin on descent stage

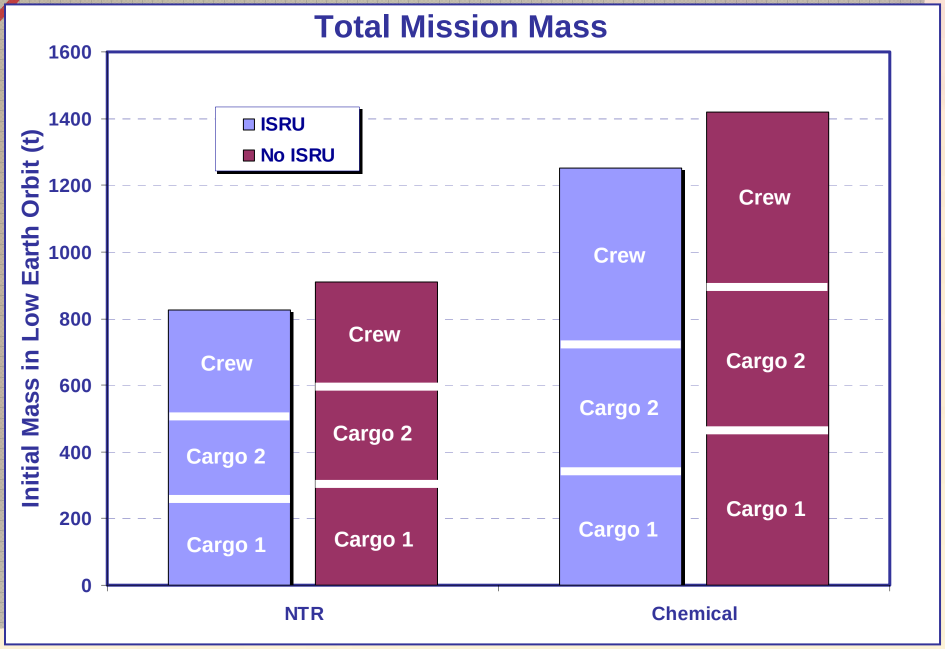
No ISRU (Earth Propellants)		
Ascent Stage 2	18,550	kg
Ascent Stage 1	27,900	kg
Minimal Habitat	5,700	kg
Landed Payload	52,150	kg
Descent Stage	27,300	kg
Total Lander Wet Mass	**79,450**	**kg**

With ISRU (Earth Methane Only)		
Ascent Stage 2	9,350	kg
Ascent Stage 1	12,200	kg
ISRU & Power	11,300	kg
Landed Payload	32,850	kg
Descent Stage	21,300	kg
Total Lander Wet Mass	**54,150**	**kg**

* Wet mass; does not include EDL System
† Packaging not yet addressed







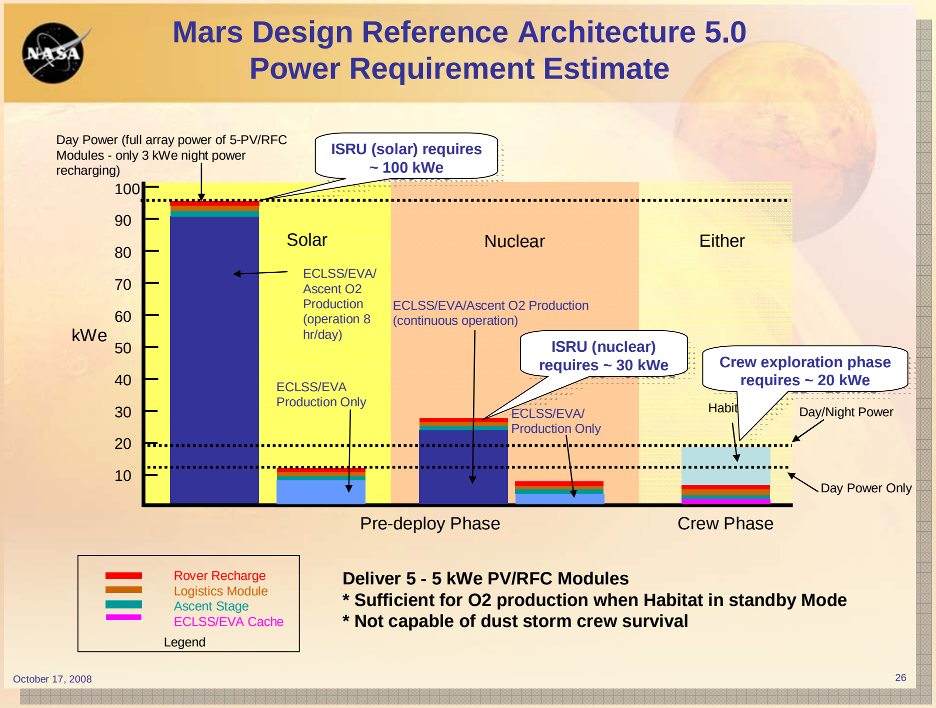
Significant mass (32%) and volume savings by producing ascent oxygen from the atmosphere of Mars

Mars Design Reference Architecture 5.0
2007 Key Decision Packages – Surface Power

Question	Which surface power strategy provides the best balance of cost, risk, and performance?
Recommendation	**Fission Surface Power System is enabling for human exploration of Mars**
Notable Advantages of Nuclear Surface Power	• Enables in-situ resource utilization strategies • Reduced power system mass and corresponding total mission mass • Less sensitive to increase in power loads • Continuous high-power generation • Low sensitivity to environmental effects such as dust storms • No restrictions to landing site location • Less complex autonomous system deployment • Potential for synergism with lunar power approach and testing to reduce risk • Lower overall cost (assuming lunar development)
Notable Disadvantages	• Inability to repair power generation system • Increased crew radiation dose as well as operational keep-out zones • Increased development and testing complexity

Mars Design Reference Architecture 5.0
Power Requirement Estimate

- Crew exploration phase requires
  - ~ 20 kWe continuous
- ISRU power requires
  - ~ 26 kWe continuous (e.g. fission)
  - ~100 kWe peak-day (e.g. solar)
- Fission surface power system provides continuous power for less mass (35%)

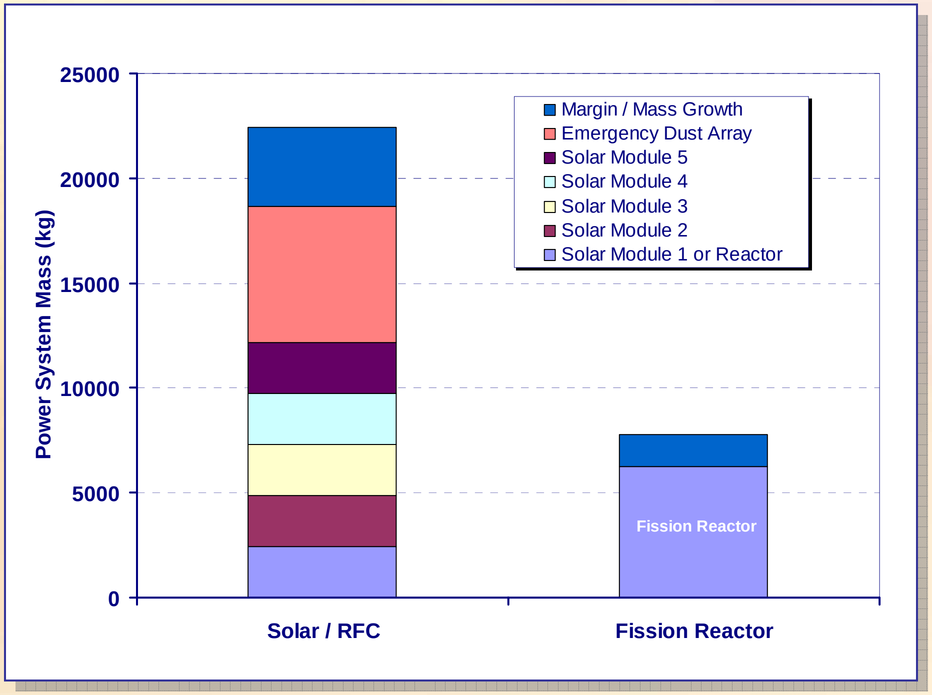


Mars Design Reference Architecture 5.0
Power Requirement Estimate

Deliver 5 - 5 kWe PV/RFC Modules
* Sufficient for O2 production when Habitat in standby Mode
* Not capable of dust storm crew survival

October 17, 2008
26

Total System Mass



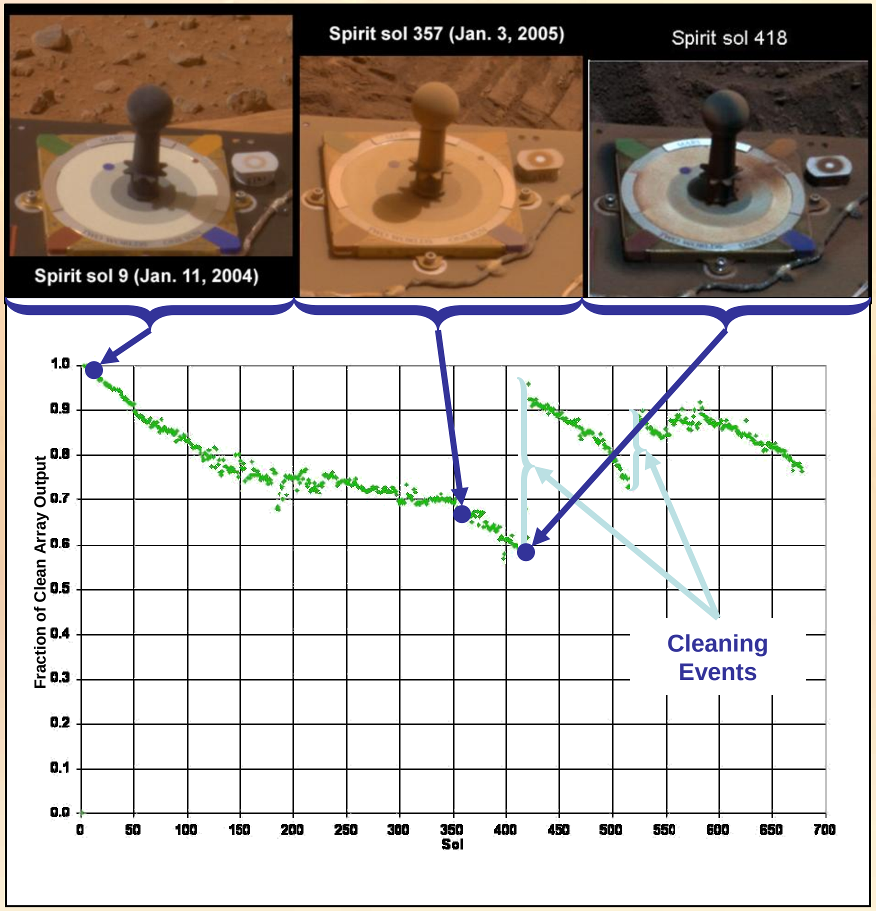
Mars Design Reference Architecture 5.0
Surface Power Special Considerations

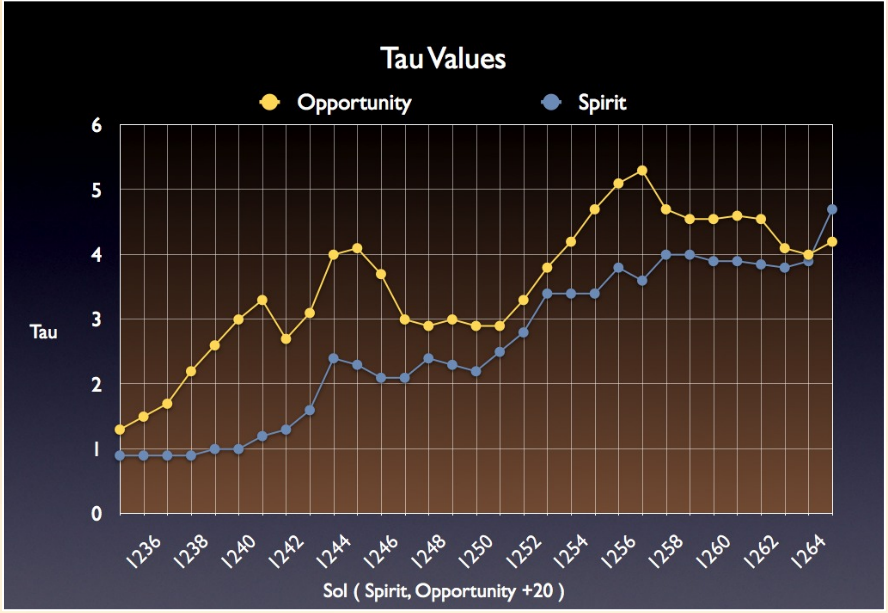
Dust Accumulation

- MER, Pathfinder ~0.2%/day output drop
- “Cleaning Events” provide temporary amelioration

Dust Storms

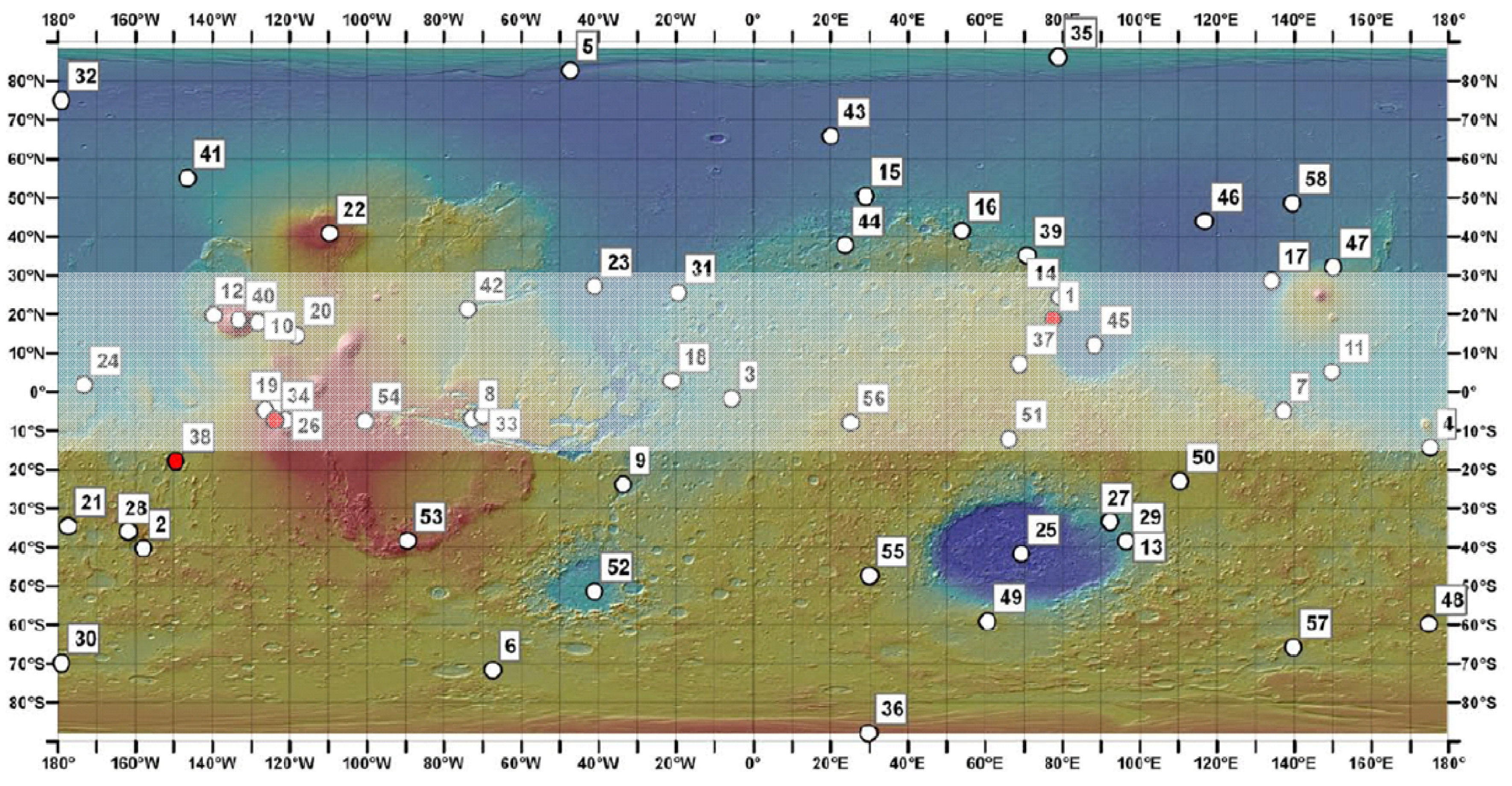
- MER dust storms dropped daily output to as low as ~15% of pre-storm capability
- Dust storms can last for one to two months, with varying degrees of obscuration at regional and sometimes global scale





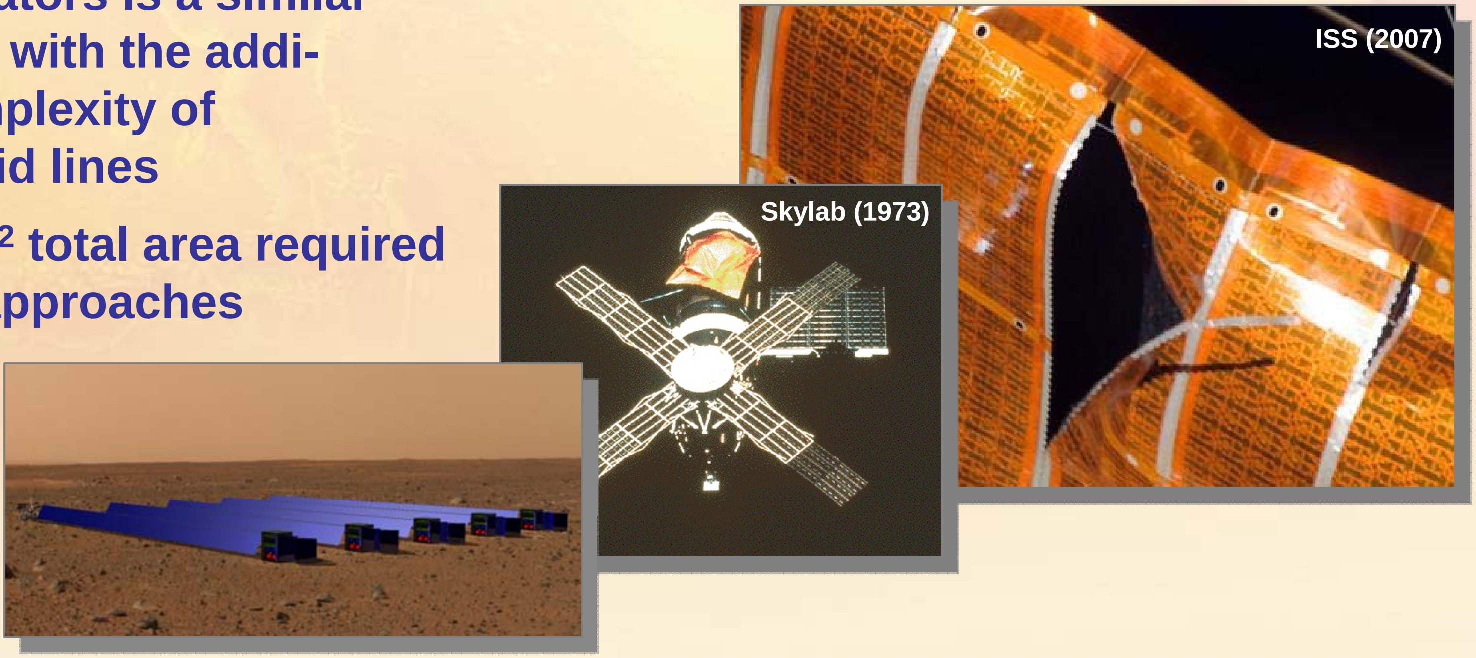
Special Consideration: Latitude Constraints

- Solar power applicability best between 15ºS and 30ºN latitudes
  - System efficiency drops quickly beyond outside this band
  - Covers 26-28 of the 58 sites of potential interest identified by HEM-SAG



Special Consideration: Deployment

- **Autonomous deployment of large structures is inherently complicated, especially in a gravity field**
  - **Solar array deployment is relatively straightforward, but the sheer size of the arrays makes this task problematic**
    - It is of note that Skylab, Mir and Space Station have experienced serious problems with solar array deployment requiring crew intervention
  - **Deployment of the large FSPS radiators is a similar operation, with the additional complexity of jointed fluid lines**
  - **~5,7500 M^2 total area required for solar approaches**

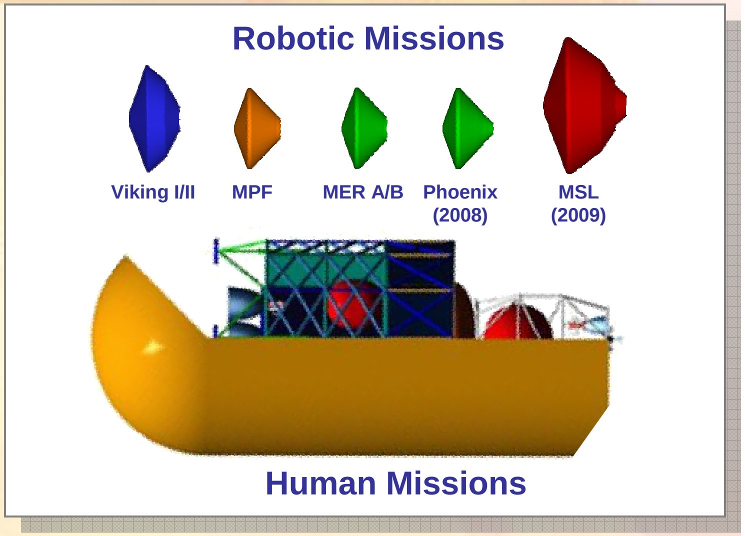


Mars Design Reference 5.0

Special Topics

- Entry, Descent, and Landing Challenges
- In-Space Transportation Systems
- Launch Vehicle and Orion Assessments
- Risk and Risk Mitigation
- Key Driving Requirements and Challenges
- Lunar Linkages

Mars Entry, Descent, and Landing (EDL) History

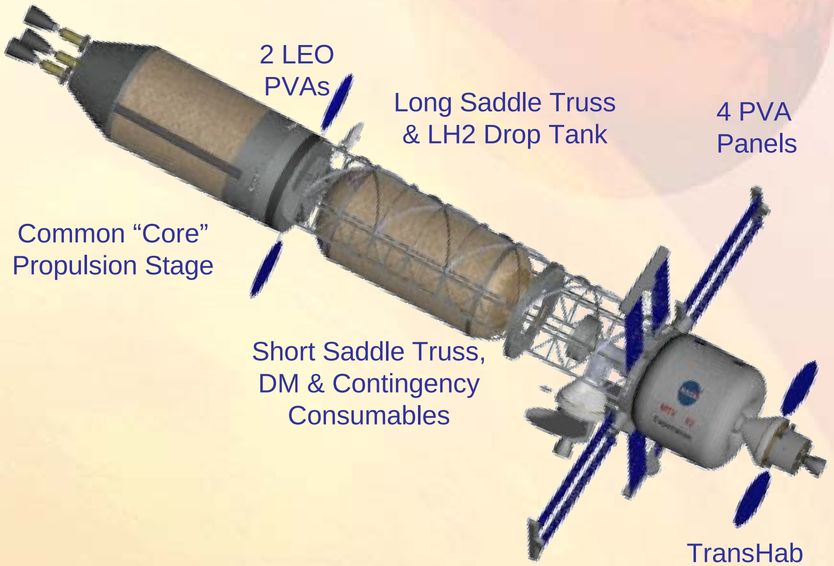


- Total of six successful robotic landings on Mars:
  - Vikings I and II (1976)
  - Mars Pathfinder (1997)
  - Mars Exploration Rovers – Spirit and Opportunity (2004)
  - Phoenix Polar Lander (2008)
- All of these successful systems:
  - Had landed masses of less than 0.6 t
  - Landed at low elevation sites (below –1 km MOLA)
  - Had large uncertainty in landing location (uncertainty in targeting predetermined landing site of 100s km)
- Mars Science Laboratory (MSL) has reached the limits of the current EDL technology set, with very limited extension available
  - 0.9 t landed mass
  - Largest aeroshell (4.5m) ever flown
  - Largest ballistic coefficient (140+ kg/m2) ever at Mars
  - Highest heat rate (250 W/m2 , using PICA TPS)
  - Largest supersonic disk-gap-band parachute ever flow (21.5m); deployed at highest Mach number (2.2)
  - 10 km radius landing uncertainty ellipse
- Estimated landed payload mass extensibility of the MSL EDL architecture: ~2 t (max)
- Robotic Mars Sample Return (MSR) will likely require 1-3 t of landed payload mass
- Human scale mission will likely require one to two orders of magnitude in landed mass capability over current MSL capability (30-60 t landed payload mass)

Mars Design Reference Architecture 5.0
Nuclear Thermal Rocket (NTR) Reference

- The crewed vehicle elements include:
  - Common “core” propulsion stage with 3 - 25 klbf NTR engines (Isp ~900 s)
  - “In-line” LH2 tank, 4-sided truss and 2 LH2 drop tanks
  - TransHab module, PVAs, & Orion CEV/SM
  - Crewed vehicle utilizes propulsive capture (PC) at Mars; also carries contingency consumables
- The cargo vehicle elements include:
  - Common “core” propulsion stage with 3 - 25 klbf NTR engines (Isp ~900 s)
  - Core stage propellant loading augmented with “in-line” LH2 tank for TMI maneuver
  - Dual-use aeroshell used to aerocapture (AC) lander payloads into Mars orbit, then for entry, descent and landing (EDL) on Mars
- NTR cargo & crewed vehicle elements are delivered to LEO and assembled via autonomous EOR&D
- NTR stage used for R&D propulsion, orbit maintenance & electrical power (via PVAs) for the vehicle elements during LEO assembly

Crew Vehicle Elements



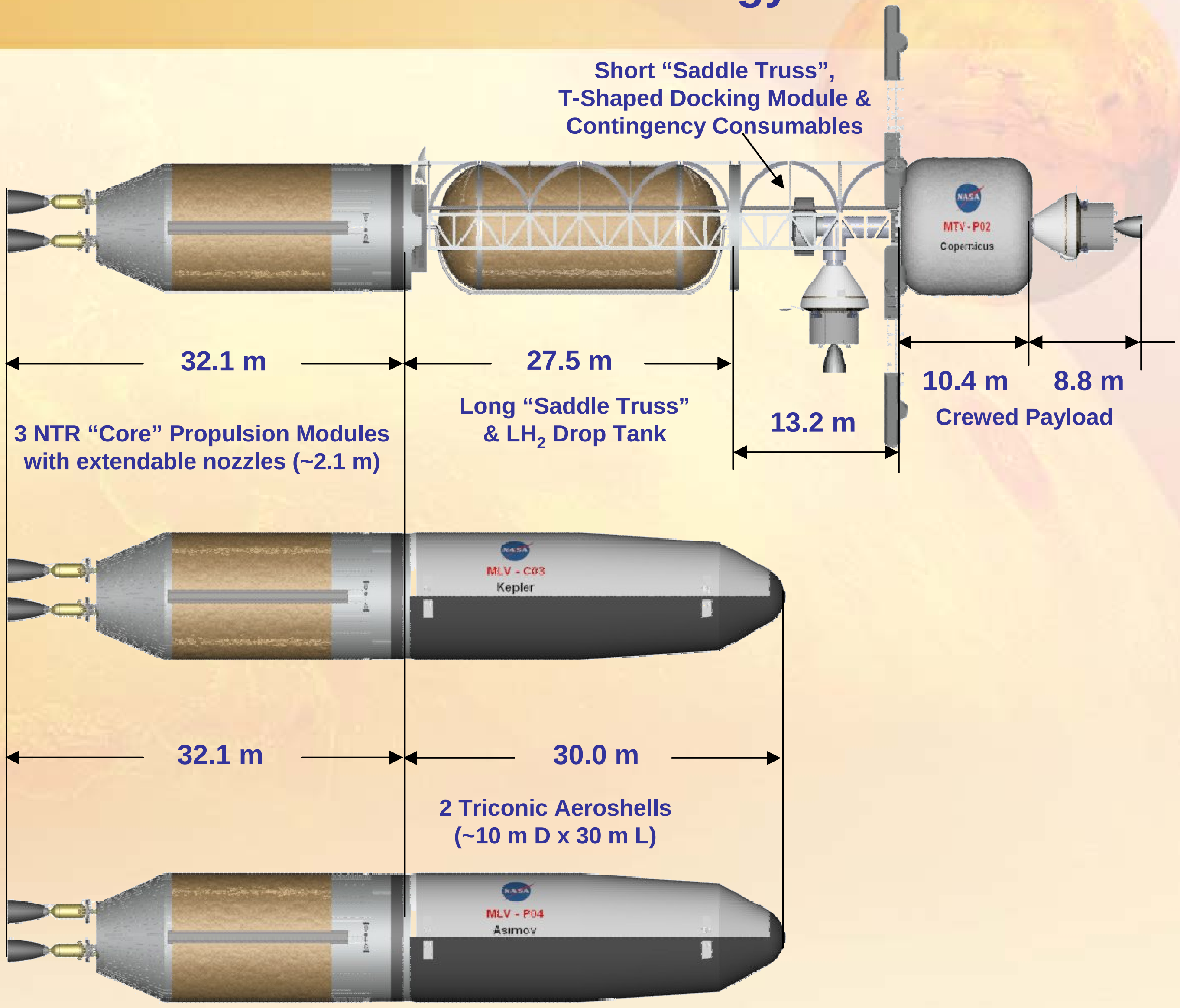
Cargo Vehicle Elements

NTR Crewed & Cargo Mars Transfer Vehicles (MTVs) for DRA 5.0: “7-Launch” Strategy

“0-g_E” Crewed MTV:
- IMLEO ~336.5 t
- 3 Ares-V Launches

Cargo Lander MTV:
- IMLEO ~233.4 t
- 2 Ares-V Launches

Habitat Lander MTV:
- IMLEO ~233.4 t
- 2 Ares-V Launches



Short “Saddle Truss”,
T-Shaped Docking Module &
Contingency Consumables

32.1 m

27.5 m

10.4 m

8.8 m

Crewed Payload

13.2 m

Long “Saddle Truss”
& LH_2 Drop Tank

3 NTR “Core” Propulsion Modules
with extendable nozzles (~2.1 m)

32.1 m

30.0 m

2 Triconic Aeroshells
(~10 m D x 30 m L)

Source: Glenn Research Center

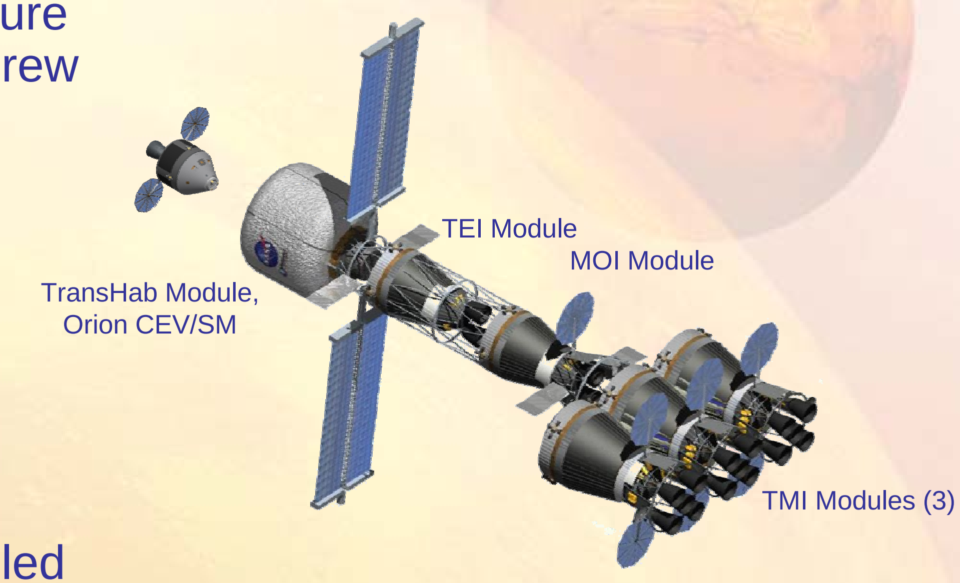
Nuclear and Solar Electric

- Direct NEP missions require megawatts of electrical power (8-20 MW)
  - Solar arrays generating this much power may not be feasible
- Direct NEP requires very high-power, high-specific impulse EP thrusters (5,000 -10,000 sec Isp)
- Using Aero-assist reduces required power to 4-5 MW and decreases optimal Isp to 4,000-7,000 sec
- Using NEP or SEP for LEO to HEO staging reduces power to < MW and decreases optimal Isp to ~3000 sec
- 100 kW class electric propulsion thrusters have seen recent developments as a result of the Prometheus & ESR&T programs
- Ground testing & propellant selection are important consideration
- Significant technical risks exist with each approach and they were thus dropped for further consideration

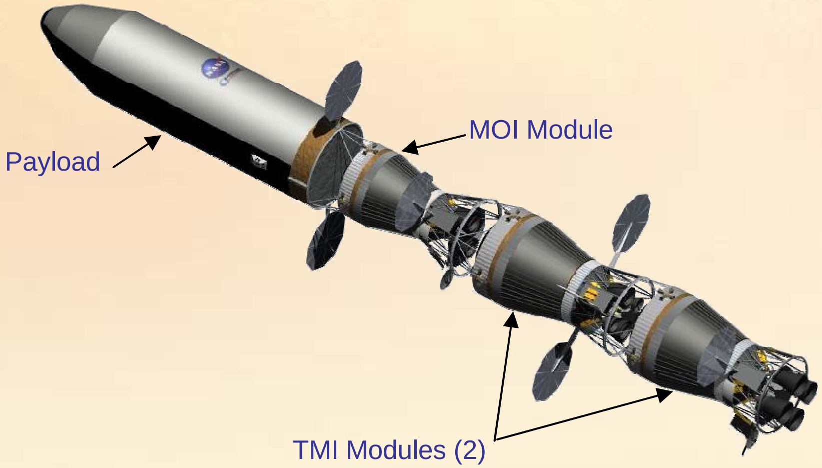
Design Reference Architecture 5.0 Chemical/Aerocapture Vehicle Option

- The chemical/aerocapture architecture consists two cargo vehicles and a crew vehicle
- Vehicle elements include:
  - TMI Propulsion Modules
  - MOI/TEI Propulsion Modules
  - Cargo Payloads
  - Crew Transit Habitat
  - LEO Assembly Reboost Modules
- Vehicles elements are fully assembled and deployed in Low earth Orbit using autonomous docking and assembly
- The LEO Assembly Reboost Modules provide orbit altitude maintenance for the vehicle elements during assembly
- Synergism of Ares V EDS for Mars mission application possible

Crew Vehicle Elements

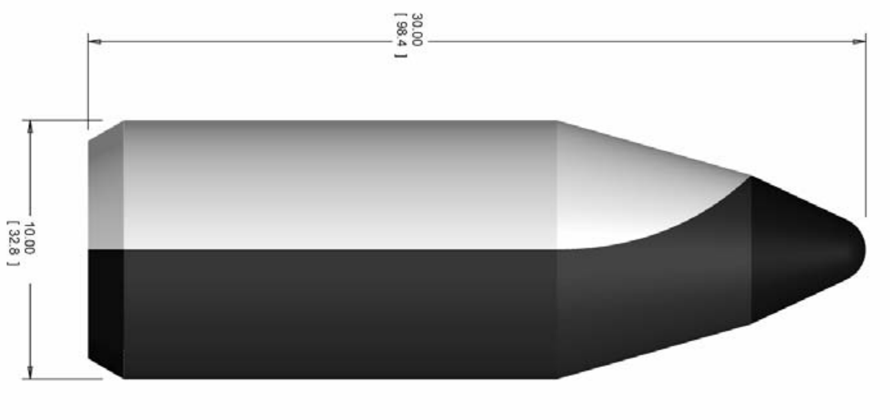


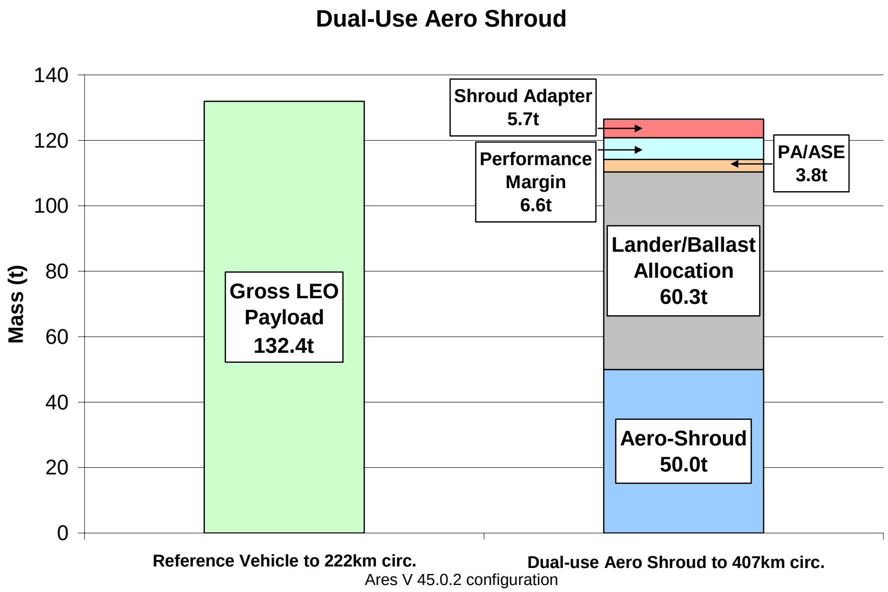
Cargo Vehicle Configuration



Mars Design Reference Architecture 5.0
Launch Vehicle Shroud

- **Minimum of 10 m payload shrouds are necessary for packaging of Entry, Descent & Landing (EDL) system and lander**
- **Dual Use Shroud:**
  - **Preliminary assessments indicate launch vehicle shroud can be used for both ascent to low-Earth orbit as well as EDL aeroshell structural element**
- **Ares-V (Dual Use Shroud) Performance to 407 km LEO orbit**
  - **110.3 t for Shroud/EDL and payload**
  - **16.1 t additional allocation for payload adapter, airborne support equipment and margin**

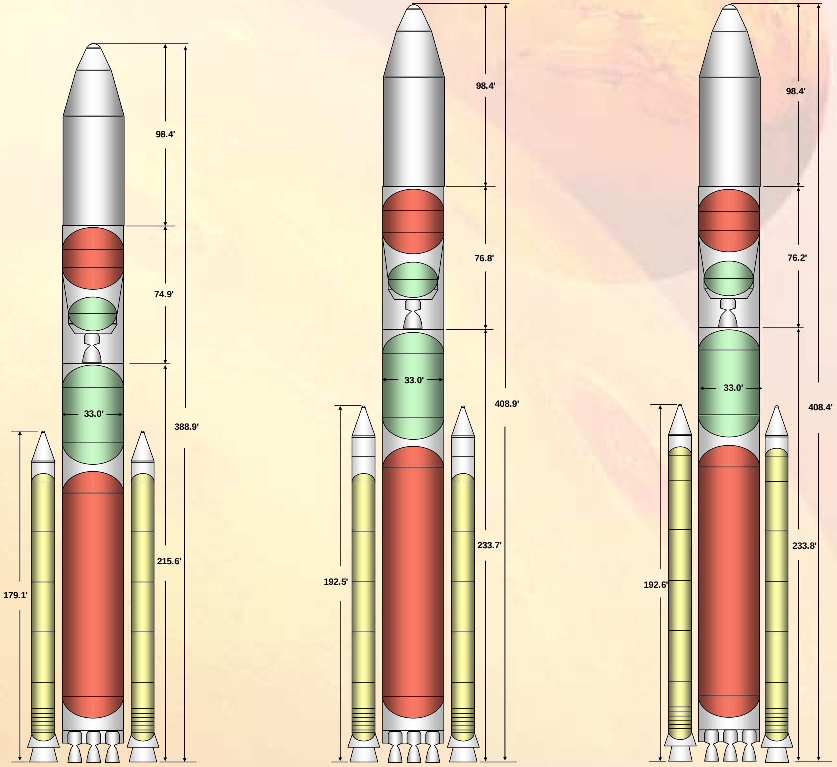



Dual-Use Aero Shroud

Ares V 45.0.2 configuration

Ares-V 51.xx Series Performance

- Follow-on analysis of CxAT_Lunar launch concepts applicability to Mars
- 51 series of Ares-V launch vehicles provides better performance to LEO
- Use of off-loaded lunar-derivative EDS reduces available shroud volume
- Payload shroud volume limits inhibit maximum performance to Mars
- Forward Work: Optimize EDS for LEO delivery missions and reduce stack height

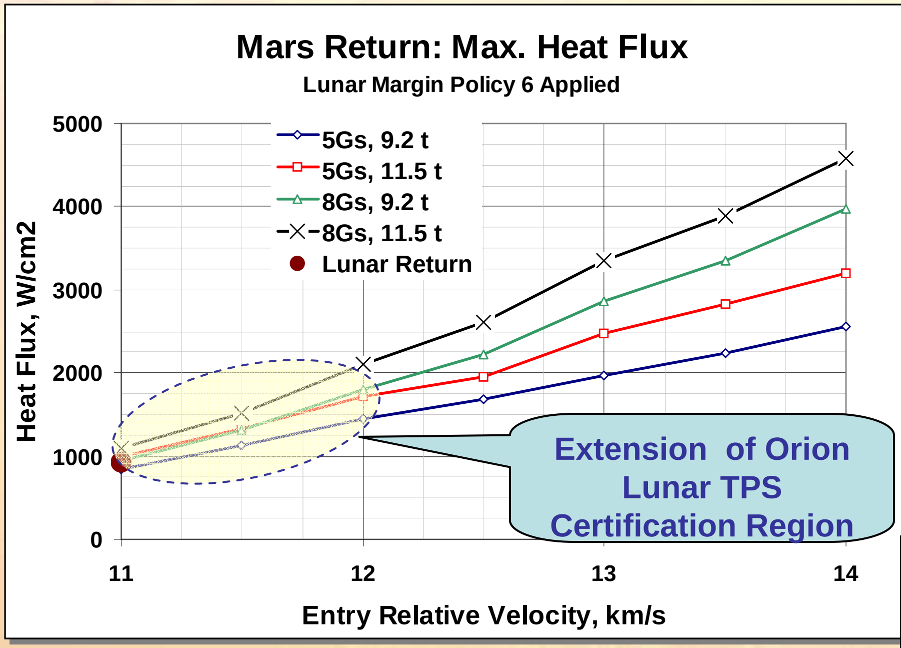


Assumed Shroud:
Outer Diameter: 10 m
Barrel Length: 18 m
Overall Length: 30 m

	51.00.40	51.00.47	51.00.48
Jettison Shroud			
Payload to LEO (t)	126.4	136.9	130.8
Dual-Use Shroud			
Payload (lander) to LEO (t)	79.0	89.6	83.6
Shroud to LEO (t)	50.0	50.0	50.0

LEO defined as 407 km circular

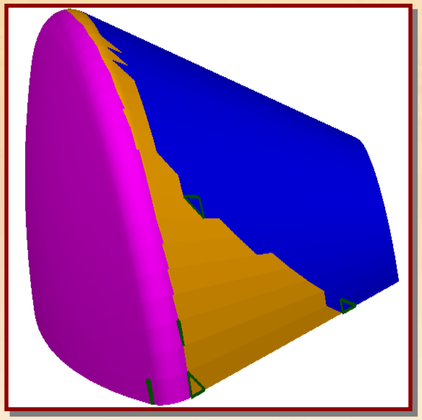
Orion Earth Return Speeds Drive Block 3 TPS Development Requirements

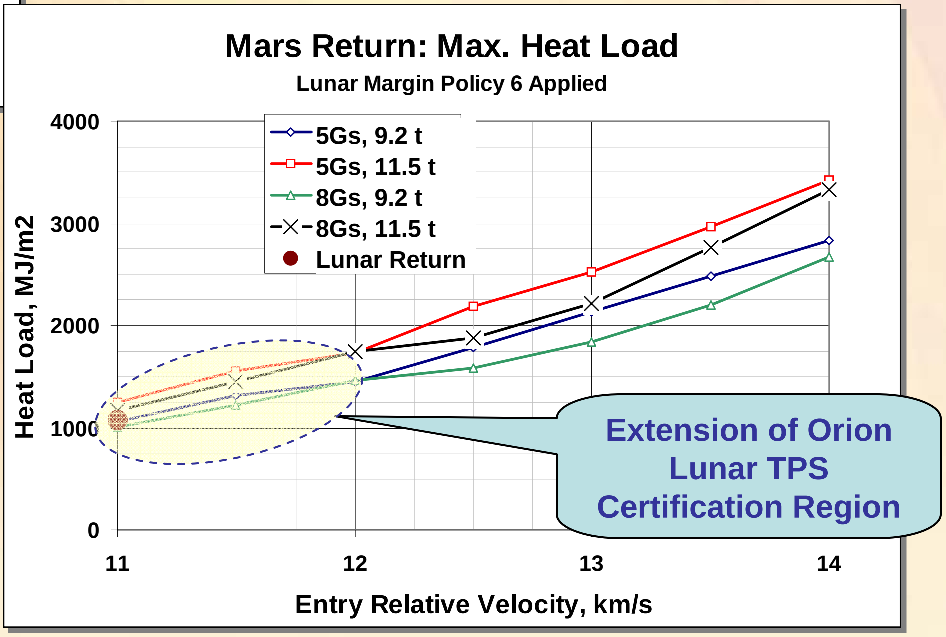


- Limiting Earth return velocities to <12 km/s keeps TPS requirements “within Orion family”.
- At 12 km/s, peak margined heating rates are ~1,700 W/cm² (current ground test capability is limited. Comfort zone for ADP is 1,000 W/cm²)
- At and beyond 12 km/s, radiative heating is a major driver for TPS mass (need to continue to pursue coupled convective/radiative heating modeling and work on advanced TPS)

Split Line
12 km/sec

PICA
SLA
BRI-8

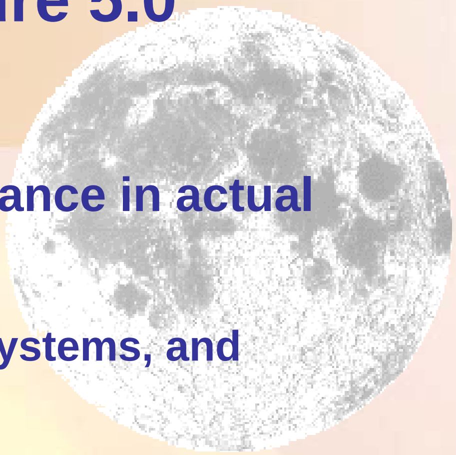




Mars Design Reference Architecture 5.0
Risk Assessments and Mitigation

- Focused on top-level risk assessments to drive out relative architectural differences
- Key Risk Drivers Identified to Date (not in priority order):
  - Entry Descent and Landing
  - Other dynamic events: Trans-Mars Injection, Mars Ascent, Trans-Earth Injection
  - Time on systems and reliability
  - Failure of systems which must operate without crew repair ability (e.g. crew Mars Transfer Vehicle during surface mission)
  - Development risk of nuclear propulsion and power and In-Situ Resource Utilization
  - Radiation protection and radiation environment on Mars
- Key Risk Mitigation Strategies
  - A rich, “Mars Like” lunar program which demonstrates key system behavior, operability, repair (life support, propulsion, power, etc.) and time on systems
  - A Mars Robotic Program which obtains key engineering data and demonstrates scalable human exploration systems and concepts
  - Supportability and Commonality concepts for in-flight maintenance and repair of low-level component and systems
- Refinement of risk assessments will require greater understanding of the Mars systems designs. Recommend further refinement of all Mars systems to improve our understanding.

Mars Design Reference Architecture 5.0
Testing on the Moon



- Lunar surface tests can demonstrate system performance in actual space environments
  - Advanced power, habitation, life support systems
  - Science campaigns and instruments, surface mobility systems, and operational planning
  - Dust mitigation techniques
  - Radiation protection
  - Advanced operations and automation (minimal/no surface assembly)
  - In-situ resource utilization
  - Terminal descent and hazard avoidance
  - Science and operational concepts
- Lunar surface missions will prove useful as long-term “dry run” rehearsals and “what if” scenarios for future human Mars missions
- Long-term exposure of systems to the deep-space environment, including radiation, can be demonstrated
- Lunar surface operation will provide valuable data on component performance in dusty environments
- Demonstration of in-situ repair and maintenance techniques and technologies
- Operational experience on full-scale systems could be collected and evaluated prior to system deployment on a Mars mission

Mars Design Reference Architecture 5.0
Key Driving Requirements (KDR) & Challenges

- **Ground Ops**
  - 7+ launches per mission
  - 30 day launch centers (300 day launch campaign)
  - Processing of nuclear systems
  - Ares-V launch vehicle configuration
  - Production and storage of cryogenics and helium
- **Ares-V**
  - 10-m dia x 30 m total length launch shroud
  - Dual use shroud (EDL)
  - 125+ t to LEO
  - Launch to higher inclinations
  - EDS evolution to long-duration (option)
- **Cross-cutting**
  - Automated Rendezvous & Docking (in Earth orbit)
  - Cryogenic fluid management (H_2, O_2, CH_4)
  - Commonality & lowest level maintenance & repair
  - Long-term system operation (300-1200 days)
  - Low-Earth Orbit loiter for 300+ days
  - Planetary protection
  - Dust mitigation
- **Mobility and Exploration**
  - 100+ km roving range
  - 10+ m depth access
  - Light-weight, dexterous, maintainable EVA
  - In-situ laboratory analysis capabilities
- **Human Health & Support**
  - Support humans in space for 900 days
  - Radiation protection & forecasting
  - Zero-g countermeasures
  - Closed-loop life support (air & water)
- **In-Space Transportation**
  - ~50 t roundtrip (LEO to Mars orbit return)
  - 110 – 125 t to Trans-Mars Injection
  - Assembly via docking only
  - ISRU compatible lander propulsion (oxygen)
  - Integrated transportation flight experience
  - Advanced Inter-planetary Propulsion
- **Aeroassist**
  - 40-50 t payload to the surface
  - Aerocapture + EDL for cargo
  - Abort-to-Mars surface
  - 12 km/s Earth return speed
- **Surface Related**
  - Auto-deployment and checkout of systems 30+ kWe continuous power
  - Reliable back-up power system
- **ISRU**
  - Extraction, storage and use of consumables from the martian atmosphere
  - Production of 24 t of oxygen for ascent
  - Production of life support oxygen (2 t) and water (3.5 t)

Mars Design Reference Architecture 5.0
Moon – Mars Transportation Linkages

System	Lunar / ISS	Mars
Ares I	♦ Launch Orion and crew to LEO	♦ Launch Block 3 Orion and crew to LEO
Ares V	♦ 71.1 t to TLI (130 t to LEO) ♦ 10 m diameter x 9.7 m barrel length shroud ♦ 2-4 launches per year	♦ 125+ t to LEO ♦ 10 m diameter x 30 m barrel length shroud, dual use shroud ♦ 7+ launches on 30-day centers
Orion	♦ 6 crew to LEO or 4 to/from LLO ♦ 11 km/s entry speed ♦ 180 day dormancy	♦ 6 crew direct Earth return (3 days active) ♦ Advanced TPS for 12 km/s entry speed ♦ 900- day dormancy
Altair Descent Stage	♦ All propulsive descent and landing ♦ 2030 m/s delta-v with hazard avoidance ♦ LO_2/LH_2 propellants	♦ Aerodynamic entry, propulsive landing ♦ 700 m/s delta-v with hazard avoidance ♦ LO_2/LCH_4 propellants
Altair Ascent Stage	♦ 4 crew to Low-lunar orbit ♦ 1900 m/s ascent delta-v ♦ Vacuum ascent ♦ N_2O_4/MMH or LO_2/LCH_4 propellants ♦ Earth propellants for ascent ♦ 210 days on lunar surface ♦ 14.5 t payload (cargo mode) ♦ Descent abort: Abort to orbit	♦ 6 crew to high-Mars orbit ♦ 6500 m/s ascent delta-v ♦ Aerodynamic ascent ♦ LO_2/LCH_4 propellants ♦ Mars produced oxygen for ascent ♦ 1200 days on martian surface ♦ 40+ t payload capability (cargo mode) ♦ Descent abort: Abort to surface

Mars Design Reference Architecture 5.0
Moon – Mars Surface System Linkages

System	Lunar	Mars
EVA	♦ Lunar environment	♦ Mars environment ♦ Minimized contamination
Small Pressurized Rovers	♦ 100+ km surface range ♦ 2 crew for 1-2 week duration	♦ 100+ km surface range ♦ 2 crew for 1-2 week duration
Surface Habitation	♦ 4 crew for up to 180 days => Continuous ♦ Multiple elements, surface assembly	♦ 6 crew for up to 550 days ♦ Single element, deployment
Environmental Control & Life Support	♦ Partially closed air and water ♦ ISRU (Oxygen) enhancing	♦ Closed-loop air and water ♦ ISRU (O_2, H_2O, N_2, Ar) enabling for robust exploration
In-Situ Resource Utilization	♦ Architecture enhancing, Soil based ♦ Utilized for life support make-up ♦ Potential H_2O from cold traps	♦ Architecture enabling, Atmospheric based ♦ Oxygen for Mars ascent, H_2O, O_2, N_2, Ar for EVA and life support ♦ Option for hydrated minerals or sub-surface water
Surface Stationary Power	♦ 35 kWe daytime total load ♦ Solar PVA/RFC primary, Multi unit ♦ Fission surface power system option	♦ 30 kWe continuous load ♦ Fission surface power system primary ♦ Must accommodate dust and dust storms
Operations	♦ Semi-autonomous – minimal time delay ♦ Limited logistics resupply	♦ Fully autonomous – long time delay ♦ No logistics resupply

Forward Work

- **Further integration, assessment and refinement of lunar surface systems and strategies which can feed forward to Mars**
  - **Habitation systems and life support**
  - **EVA and surface mobility**
  - **Nuclear surface power**
  - **In-situ Resource Utilization**
  - **Lander oxygen-based propulsion**
  - **Commonality and in-flight maintenance & repair approaches**
  - **Science and operational concepts**
- **Further refinement of Ares-V launch approach**
  - **Dual-use shrouds**
  - **Ground operations processing concepts and campaign assessments**
- **Coordinated, Agency-wide, EDL development effort for landing large payloads (fundamental aero, integrated Ares V shroud/lander design, etc.)**
- **Deepen understanding of risk drivers and methods to obviate risks**
  - **Reliability Drivers**
  - **Maturity Process**
  - **Precursor Activities**
- **Technology development roadmaps and precursor assessments**
- **Address options for reducing total mission mass and thus number of launches**
- **Quantitatively tie precursor program and flight tests to risk mitigation**
- **Maximize synergy with Mars robotic program including landing large payloads**