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# Human Mars Exploration Transportation: Bridging Concept of Operations

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**A bridging architecture between a sustained Lunar exploration architecture and a sustained Mars transportation architecture is presented. The Mars architecture assumes sustained Mars operations as a final goal. A bridging Mars exploration transportation Concept of Operations (CONOPS) was developed. We describe the needed Earth/Moon system architecture, the sustained Mars system infrastructure, and the bridging Mars transportation infrastructure. Three trade space areas were explored including Earth node location, focal point of human Mars operations, and the level of pre-positioning of assets. Options are compared for the focus of long-term human Mars operations including on the Martian surface, in some high Mars orbit station or on a satellite like Phobos. Operational aspects are discussed including the role of teleoperation techniques, planet-wide human sorties versus operations from a fixed site, the impact of the long-duration low-g environment, transportation system requirements, and potential resource utilization. We also provide information on required new technologies, and make recommendations for an overall human transportation concept.**



## I. Introduction

In support of the Mars Transportation System Architecture portion of an Orbital Sciences Concept Exploration and Refinement (CE&R) study, Global Aerospace Corporation (GAC) developed a bridging architecture between Orbital's Lunar Architecture (Ref. 1, 2) and a sustained Mars Transportation Architecture that was previously developed by GAC under NASA Institute for Advanced Concepts (NIAC) funding. (Ref. 3, 4). Orbital's Lunar Architecture ended at sustained lunar operations while the GAC Mars architecture assumed sustained Mars operations as a final goal.) Both the bridging and the sustained Mars exploration transportation Concept of Operations (CONOPS) were developed. Five trade space areas were explored and three are discussed here including Earth node location (L-1, Low Lunar orbit radius, other), focal point of Mars ops (Mars surface, Phobos, low Mars orbit), and the level of pre-positioning of assets. In this paper, we describe the needed Earth/Moon system architecture, the Mars system infrastructure, and the Earth/Mars system infrastructure. We also summarize recommendations regarding a Mars concept of operations including the need for robotic precursors; the development of a resonant orbit transportation architecture; the pre-positioning of infrastructure and logistics at Mars; the placement of the Earth and Mars transport nodes; the role of teleoperation; the use of aerocapture systems; the transport of cargo; and the placement of spaceport platforms at Earth and Mars transport nodes.

## II. Sustained Lunar and Mars Exploration Transportation Baselines

In this section we summarize the basis for the bridging Mars transportation architecture that is based on a sustained lunar exploration transportation architecture developed by Orbital under contract to NASA and a sustained Mars transportation architecture developed by GAC under contract to NIAC.

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### A. Lunar Exploration Transportation Architecture

From 2004 September 1 until 2005 September 9, Orbital Sciences conducted a NASA-funded Concept Exploration and Refinement (CE&R) study (Ref. 1, 2), designed to make recommendations on how to return humans to the Moon. An all chemical Lunar Transportation system consisting of a Shuttle Derived Heavy Lift Launch Vehicle (SDHLLV), a Crew Module (CM), a Space Exploration Module (SEM), an in-space propulsion system, and a single stage reusable Lunar Lander, was designed. This optimized transportation system can deliver 140 mt to Low Earth Orbit (LEO), 38.8 mt (85,600 lbm) to Low Lunar Orbit (LLO), and 15.9 mt (35,000 lbm) to the Lunar Surface. This architecture requires two launches: the first launch places the Lander in LLO, and the second launch places the CM in LLO. The Lunar Surface Activity fundamental objective was to construct and operate a Lunar Base with permanent crewed capability. All items needed to construct and operate the base, along with propellants, human consumables and base spares for base operation were manifested onto a Lunar Exploration campaign. A Crew Survival Infrastructure, consisting of an abort mode strategy; safe haven distribution; crew rescue strategy; space weather monitoring, prediction and alert system; and contingency planning was included in the Lunar Exploration Architecture.

As shown in Figure 1 and Figure 2, the Concept of Operations (CONOPS) is as follows. The first of two launches has a payload consisting of the Human Lunar Lander (HLL). The SDHLLV/SEM combination places the HLL first in LEO, then the SEM transfers the HLL to LLO. After successful checkout of the HLL in LLO, the second launch occurs. The payload is the CM, containing four astronauts. The SDHLLV/SEM places the CM in LEO. The SEM transfers the CM to LLO. Prior to CM arrival in LLO, the HLL and its SEM demate. The CM rendezvous with the HLL in LLO. The four astronauts transfer from the CM to the HLL. The HLL demates from the CM/SEM, and lands on the surface of the Moon. After a successful mission, the four astronauts re-enter the HLL, and ascend to the waiting CM/SEM in LLO. The HLL mates with the CM/SEM. The astronauts transfer back into the CM, the HLL demates, and the SEM executes the TEI burn, to bring the astronauts back to Earth via Direct Entry. Upon entering the Earth's atmosphere, the ablative heat shield dissipates the heat produced by high speed contact with the atmosphere. After sufficient reduction in speed, three steerable drogue parachutes deploy, and the CM lands at a pre-determined location on land.

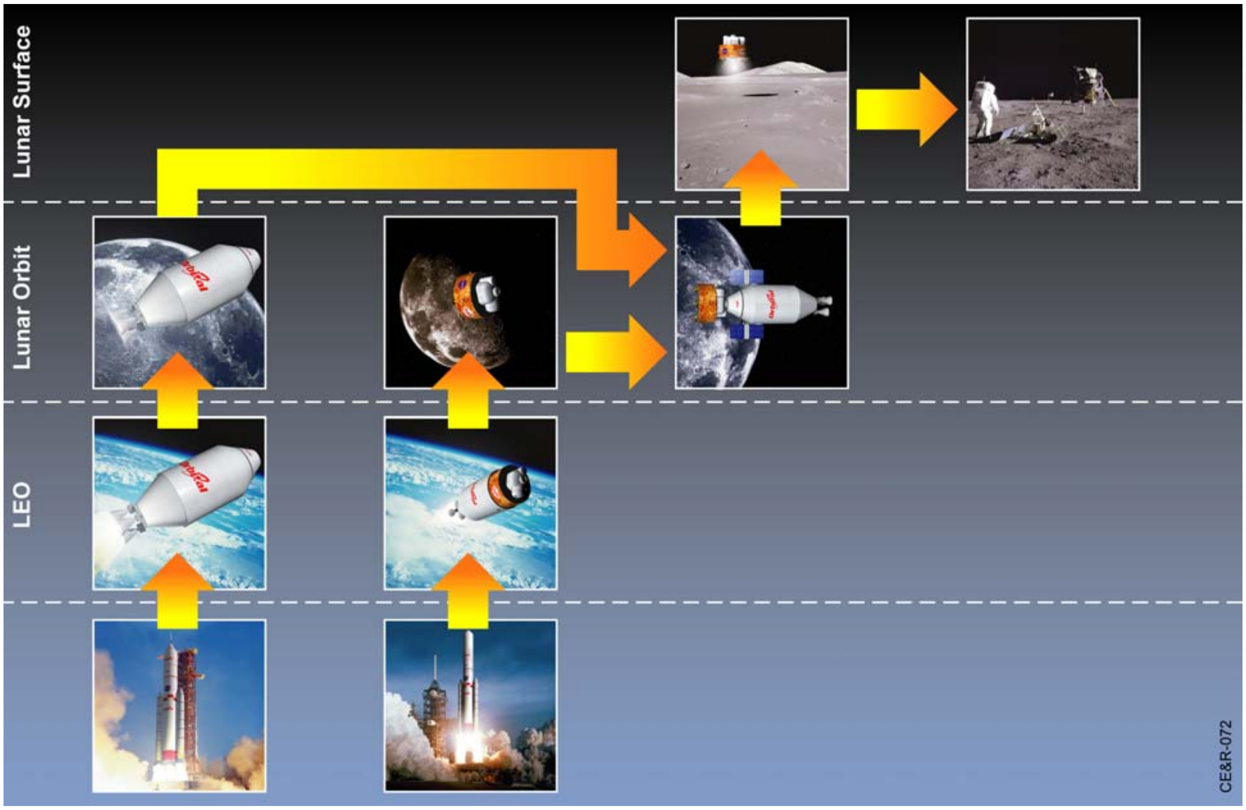


**Figure 1. Lunar transportation CONOPS - Earth to Lunar surface**

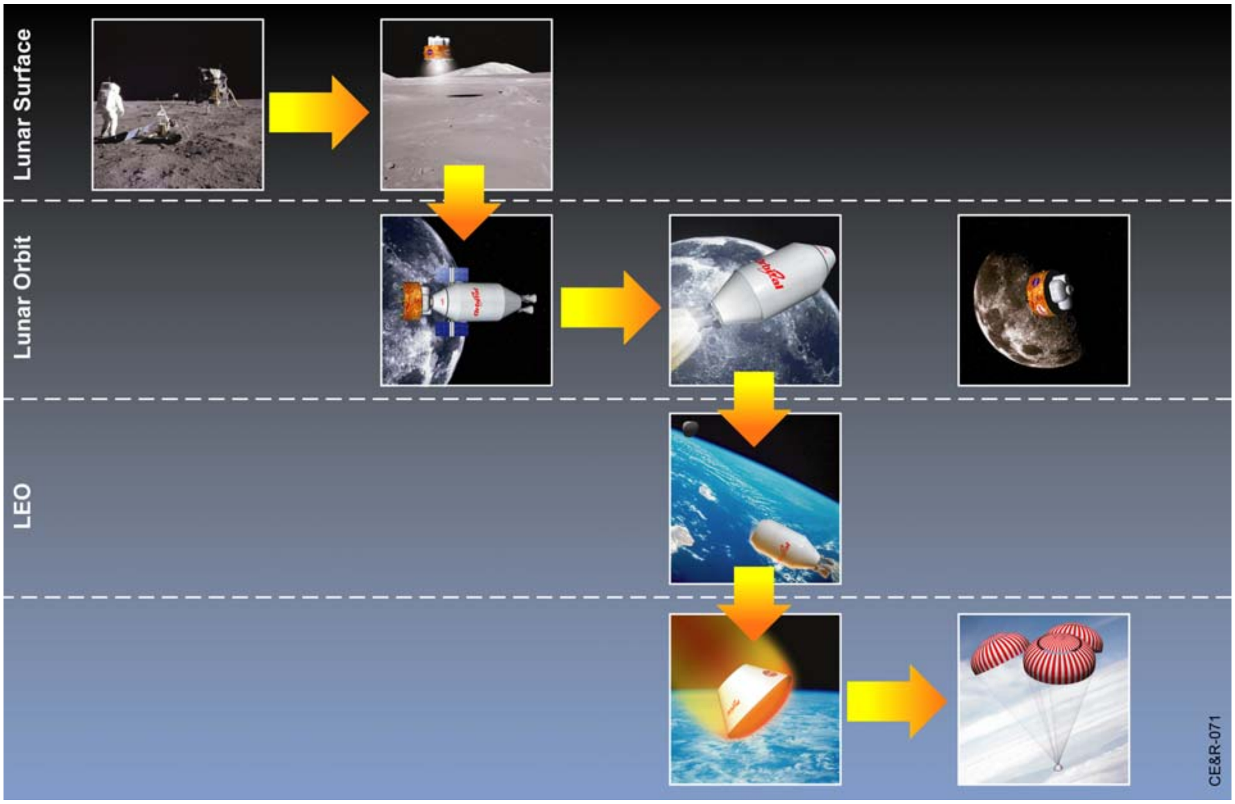


**Figure 2. Lunar transportation CONOPS - Lunar surface to Earth**

The recommended layout of the Lunar Base is shown in Figure 3. Each module has at least two airlocks attached. Each airlock has four ingress/egress ports. One result of the man-rating process is there must be at least two ways to exit each habitable volume, in the event of emergency. The human and cargo landing sites must be far enough away from the inhabited portion of the base so that it does not become covered in Lunar dust from the landing and takeoff operations. If undertaken, $LO_2$ production and storage facilities should be located between the Habitable Modules and the landing sites, so as to be able to supply both with $LO_2$. The primary and secondary power plants should be on the opposite side of the base from the landing sites, both for safety reasons, and so that Lunar dust does not unduly cover the solar array panels. Figure 4 shows a 3D color rendered illustration of portions of the Lunar Base.

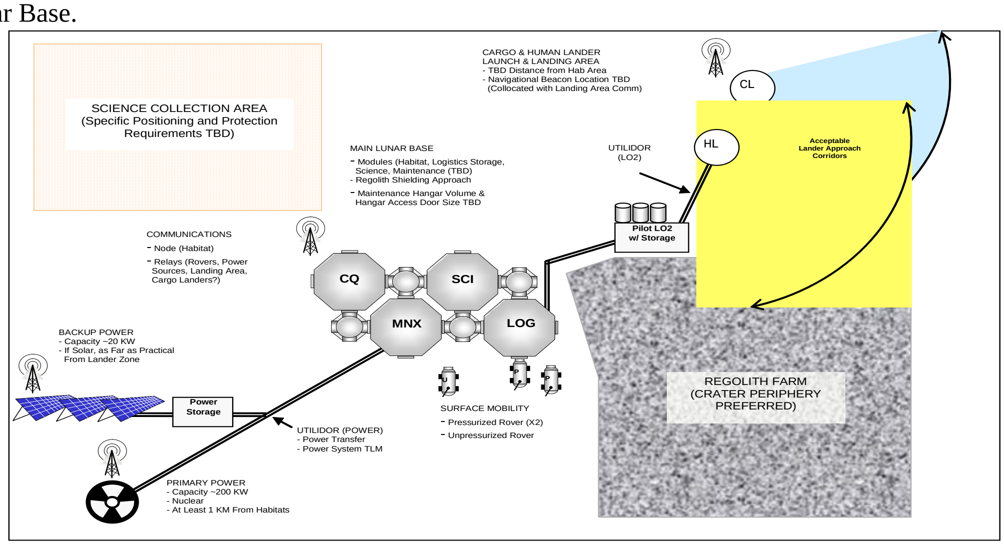


**Figure 3. Lunar Base Layout**

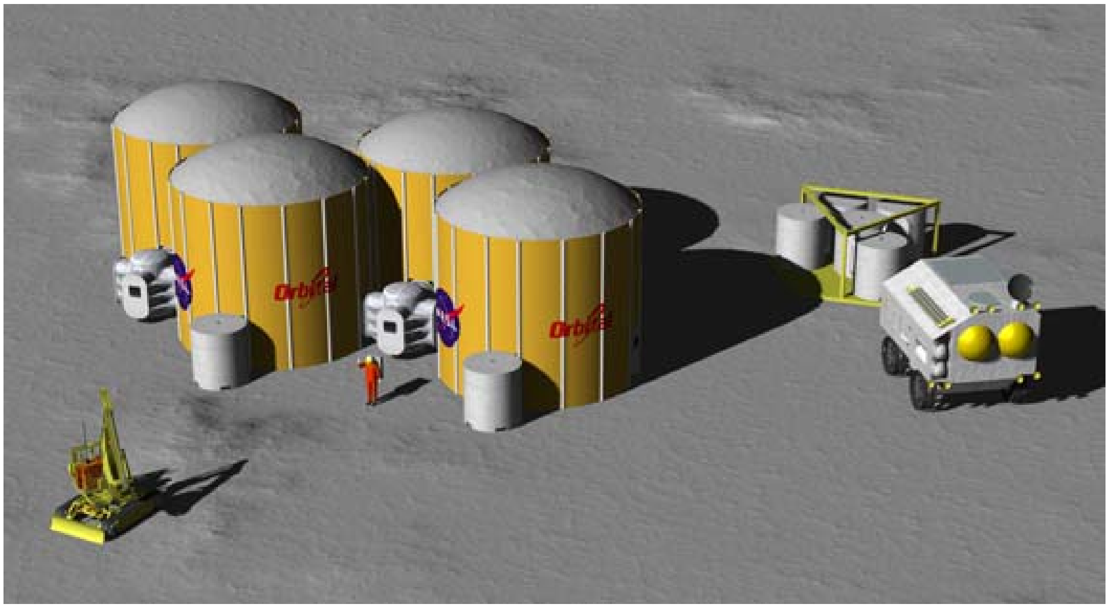

**Figure 4. 3D Lunar Base Rendering**

### B. Mars Exploration Transportation Architecture

This architecture, which is the result of work funded by the NASA Institute of Advanced Concepts (NIAC) (Ref 3, 4) uses highly autonomous, solar-powered, xenon ion-propelled Astronaut Hotels, dubbed Astrotels; small aerocapture-capable Taxis vehicles for trips between Astrotels and planetary Spaceports; planetary Shuttles that transport crews to and from orbital space stations and planetary surfaces; and xenon ion-propelled low-thrust cargo freighters that deliver hardware, fuels and consumables to Astrotels and Spaceports. The Astrotels fly between Earth and Mars in resonant so-called "Escalator" orbits; one each for the 5 month trip to Mars (the Up Escalator orbit) and for the 5 month trip return to Earth (the Down Escalator orbit). These Astrotels and Taxis enable transportation of 10-person replacement crews between Earth and Mars. Astrotels continuously loop around the Sun in Escalator orbits between Earth and Mars, while Taxis fly hyperbolic planetary aerocapture trajectories between Astrotels and Spaceports. Two crews work on Mars with alternating periods of duty, each spending about 4 years there with crew transfers occurring about every 2 1/7 years. Also discussed is *in-situ* resource utilization infrastructure including Lunar Ice Mines, Water Tankers, and Phobos LOX plants and Tankers for the mining, production, processing, and transport of water into rocket propellants and its storage; the use of aerocapture to slow Taxis, without propulsion, at the planets; and finally, the estimated total life-cycle cost of this interplanetary transportation architecture.

Figure 5 is a sketch that illustrates the overall architecture of sustained Mars transportation operations for the Up Escalator orbit to Mars flight profile. Crews start at the bottom left with launch from Earth in a Shuttle that brings them to a Space Station in low Earth orbit (LEO) where they transfer to a Taxi that takes them to the Earth Spaceport. Another Taxi propulsively departs the Earth Spaceport via a multi-impulse delta-V with a perigee burn to place it on a hyperbolic trajectory to rendezvous with one of two Astrotels that continuously loop around the Sun in resonant orbits. Five months later, nearing Mars, the crew reenters the Taxi and departs the Astrotel, using a small propulsive delta-V that targets it to an aerocapture within the Martian atmosphere. Upon exiting the atmosphere, the Taxi is on a trajectory that takes it to Phobos orbit where it propulsively circularizes and rendezvous with the Mars Spaceport. At the Mars Spaceport, the crew transfers to a Mars Shuttle that takes it to the Mars Base on the surface for its 4 year tour of duty. Also shown in Figure 5 are the resource mining and transportation infrastructure elements at the Moon and at Phobos and low-thrust Cargo Freighters that transport fuel, consumables, and refurbishment, repair and upgrade (RRU) hardware throughout the transportation architecture.

Figure 6 is another sketch that illustrates just the return of a crew from Mars via the Astrotel. The returning crew leaves the Mars Spaceport in a Taxi via a hyperbolic trajectory to rendezvous with the Down Astrotel that provides a short trip to Earth. Nearing Earth, the crew departs the Astrotel in a Taxi via a hyperbolic trajectory targeted for an aerocapture maneuver in the Earth's atmosphere. The Taxi could then go to the Earth Spaceport or go directly to the LEO Spaceport where the crew transfers to an Earth Shuttle for a return to the earth surface. Note that a bridging transportation architecture was created from two different architectures generated by two separate organizations. Hence, the terminology used is different, but described in Section III.

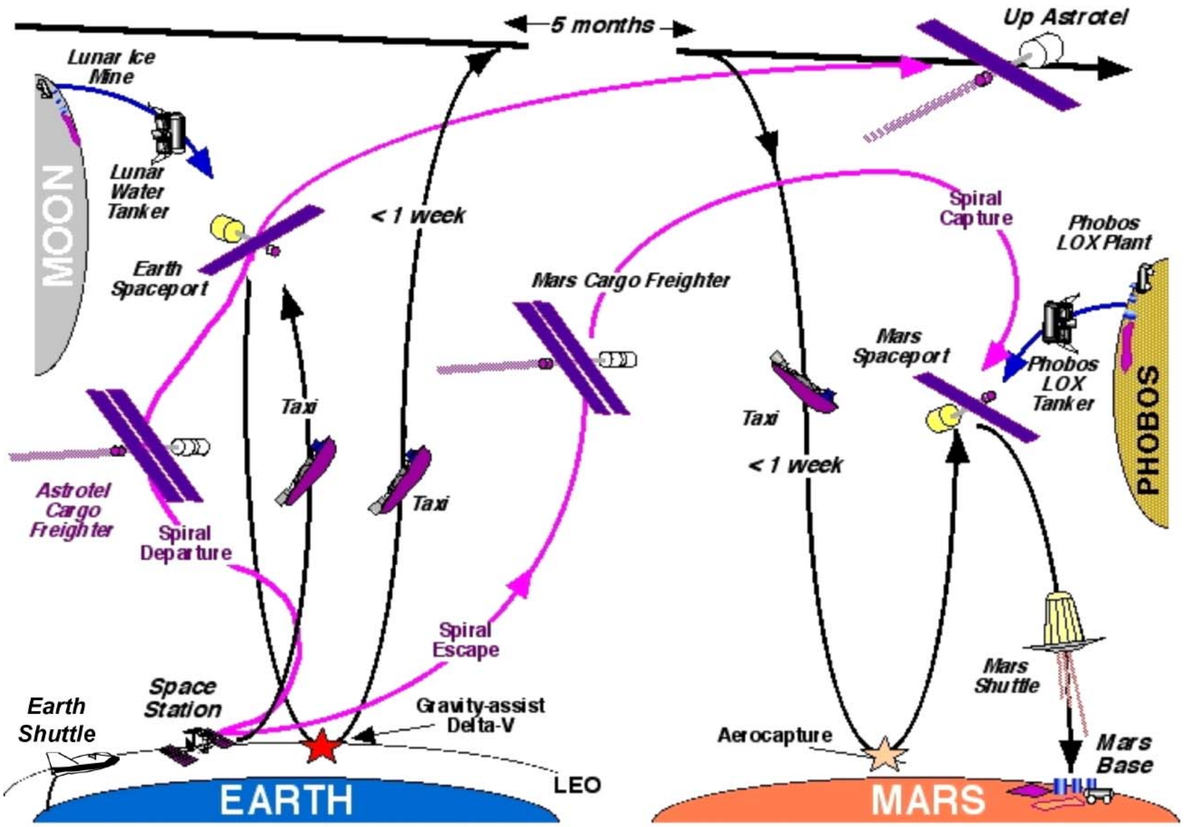


**Figure 5. Overall concept of operations for the Earth to Mars flight profile.**

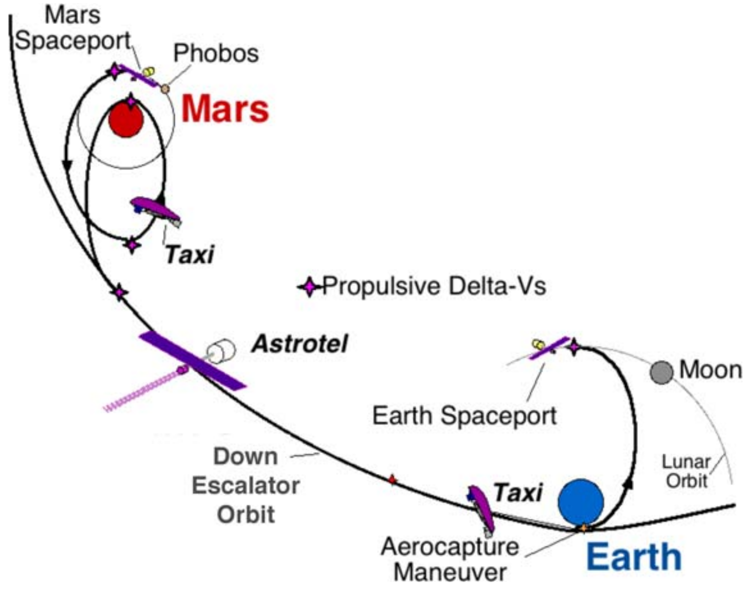


**Figure 6. Overview of crew transport from Mars to earth.**

The application of these orbital, transport vehicle and resource systems concepts serve to reduce overall mission development costs and improve overall mission reliability and safety. Once launched into resonant orbits, Astrotels can orbit the sun indefinitely while they are periodically maintained, improved, supplied with orbit correction propellants, and their cosmic ray and solar-particle radiation protection increased. As new technologies are developed, they can be incrementally incorporated if they can be shown to reduce operating costs, increase reliability or improve safety.

## III. Bridging Mars Transportation Infrastructure

The following sections describe each element of the bridging Mars transportation architecture and their heritage from the sustained lunar and Mars transportation architectures.

### A. Human Interplanetary Transport (HIT)

The Human Interplanetary Transport (HIT), also called the Astrotel in the sustained Mars architecture, will be derived from the Lunar habitat for crew accommodations. For the Escalator version of HIT, it will use a small solar electric propulsion system to carry out the periodic orbit corrections required. The resonant orbit HIT will be 60 mt without propellants or consumables. For the Stopover HIT a LOX/LH propulsions system will be utilized. The Stopover HIT will be 103 mt without propellants or consumables.

### B. Earth and Mars Spaceports

The Earth and Mars Spaceports will be derived primarily from the Human Interplanetary Transport (HIT) heritage. It, too, will have a small SEP system to carry out station-keeping and phasing orbit corrections. The Mars Spaceport will be required to have artificial gravity since the first crew to Mars will spend over a year there.

### C. Taxi

The Taxis will be Lunar CM/SEM-based with moderate lift-to-drag ratio (L/D) aerocapture capability at Mars and Earth. The desired aeroshell is a raked elliptical cone that would have a modest L/D (~0.7). The aeroshell provides a large footprint for the crew module, propulsion systems and tanks behind it during aerocapture. Propulsion is LOX/LH. Crew accommodations will be Apollo-like in volume. Life support will be similar to Apollo but advanced in technology. Crew module design must account for g-load directions for propulsive maneuvers and for aerocapture, which may be different. Taxi mass is about 16 mt dry. The Taxi will have docking capability with the HIT and Earth/Mars Spaceports. It will also have a means, when docked, to maintain propellant temperatures to avoid boil-off.

### D. Cargo Interplanetary Transport (CIT)

There are two basic types of Cargo Interplanetary Transports (CITs), namely a Mars Cargo Freighter and a Astrotel (or HIT) Cargo Freighter as they are called in the sustained Mars architecture. All CITs will utilize large, high-power, high specific impulse electric propulsion systems. The CITs that carry out the Mars infrastructure buildup are larger than the CITs that sustain the Mars Base. It was assumed that the specific mass of the power and propulsion system is 8 kg/kW (split evenly between power and propulsion) and that the power to initial mass ratio is 10 W/kg. Thus a 4.4 MW SEP system will have an initial mass of 440 mt including 252 mt of cargo, 18 mt of solar array, 18 mt of propulsion systems, 20 mt of tanks, and 131 mt of propellant. A specific impulse of 5000 s is desired for the CITs that re-supply the HITs and a specific impulse of 10,000 s for the Mars CITs.

### E. Human Mars Lander (HML)

The Human Mars Lander (HML), also called the Mars Shuttle in the sustained Mars architecture, is HLL-based with the addition of an aeroshell for direct entry into the Martian atmosphere from Phobos orbit. Such an entry is quite benign as compared to the Space Shuttle entry into Earth's atmosphere. In fact, a low-L/D, Viking aeroshell can be used along with Advanced Flexible Reusable Surface Insulation (AFRSI - silicon impregnated blankets) that are used in the lower temperature regions on the Space Shuttle. It is desirable that the aeroshell be stowable for launch or be disposable once the vehicle has landed in order to minimize the cross-section area for launch. The HML carries both crew and a small amount of cargo (<10 mt) to the surface. Crew accommodations are Apollo-like except that shielding could be reduced since travel time to and from Mars is measured in hours. At the surface, it is refueled with Martian LOX/LH.

### F. Cargo Mars Lander (CML)

The Cargo Mars Lander (CML) is HML-based without the crew accommodation. It can take up to 15 mt to the surface and return 5 mt of Martian LH to Phobos if water is not found there.

### G. Heritage of the Bridging Mars Transportation Elements

The bridging Mars transportation architecture assumes the development of several new pieces of infrastructure that could have considerable design heritage with the Lunar and Mars Exploration Architectures. These elements include the following:

**Table 1. Bridging Mars transportation elements**

| Bridging Mars Architecture Elements | Lunar Exploration Architecture Design Heritage | Mars Sustained Transportation Architecture Design Heritage |
|---|---|---|
| Taxi with raked elliptical aeroshell | SEM propulsion & CM support systems | Taxi |
| Human Interplanetary Transport (HIT) | Lunar Habitat, | Astrotel |
| Human/Cargo Mars Lander (H/CML) | Human/Cargo Lunar lander | Mars Shuttle |
| Earth/Mars Spaceports | Lunar Habitat and HIT | Earth/Mars Spaceports |
| Mars Base | Lunar Base | Mars Base |
| Phobos Oxygen Plant | Lunar Oxygen Plant | Phobos Oxygen Plant |
| Phobos Propellant Depot | None | Phobos Propellant Depot |
| Mars Surface Water Plant | None | Mars Surface Water Plant |
| Lunar Water Plant | None | Lunar Water Plant |
| Cargo Interplanetary Transport (CIT) | None | Astrotel and Interplanetary Cargo Freighters |

## IV. Transportation Architecture Assumptions, Strategies and Options

In this section we describe the transportation architecture assumptions and strategies used in the development of the bridging architecture and the transportation options that have been explored including the focus of Mars operations, whether by telepresence or in person; Earth transportation node location; electric propulsion types; and the number and modularity of cargo vehicles.

### A. Assumptions and Strategies

There were several key assumptions and strategies that guided this effort. These include:

- Key themes are safety, feasibility and affordability and growth continuity
- Pre-positioning of vehicles, consumables, *in-situ* resource utilization (ISRU) hardware and transportation elements
- Significant and decisive robotic exploration at Phobos and/or Deimos to search for water and/or determine the nature of the regolith for oxygen production
- Reliance upon in-situ resources for propellants
- Crew-aided Phobos/Mars surface facility siting, construction, operation and verification
- Standard crew size of 10
- Propulsion Systems:
  - LOX/LH high-thrust propulsion (460s specific impulse, 266 kN thrust, 7:1 mixture)
  - High-power electric propulsion (0.3-4.4 MW and 5,000-10,000s specific impulse)

### B. Options for the Focus of Mars Operations

We explored two options for the focus of human Mars operations, namely, on the surface of Mars at the Mars Base or in a habitat at or near Phobos or some other high Mars orbit (HMO). This discussion is shown in the table below.

**Table 2. Options for the focus of Mars operations**

| Phobos or other HMO | Mars Surface Base |
|---|---|
| • Teleoperate exploration on Mars surface<br>• Periodic planet-wide sorties to interesting Mars surface sites<br>• Mars Human Lander carries ascent propellant or Mars Cargo Landers pre-position propellants<br>• Zero-g environment requires artificial gravity (0.38-1.0 g) | • Teleoperate exploration on Mars surface<br>• Fixed site for direct human exploration<br>• Water Plant for Lander propulsion<br>• 0.38 g maximum, no way to increase if too small<br>• Option to grow food<br>• Regolith for shielding |

Heavy emphasis on teleoperation of exploration on the surface of Mars is expected from either location since round-trip light time is very short, the crews are not expected to be large, and the range of exploration can be significantly extended by use of teleoperated robots with the use of virtual reality (VR) technology. Wherever the operator is located at Mars, they will be expected to have a very rich VR experience assuming even modest advancements in VR technology. If the crews are situated at the Mars Base, remote travel will be limited by pressurized rover range (measured in tens to hundreds of kilometers at the most). Using the human Mars Lander in a hopping mode from the Mars Base will require the use of a lander with a fixed aeroshell since the current lander concept uses a deployable aeroshell for entry that is stowed prior to launch for the Martian surface to reduce cross-section area and drag. Significant delta-V propellant will be required for planet-wide hops necessitating pre-deployment of propellant. Sorties mounted from Phobos will be able to access anywhere on Mars. Pre-deployment of propellant will be important when visiting unimproved sites. A Phobos focus requires artificial gravity capability to mitigate the zero-g conditions. Gravity could be set at any value, subject to structural and mass considerations, between Mars and Earth g-levels. The maximum g-level available on the Martial surface is 0.38. If future experiments show that this is too low for sustained, safe human operations one might require a non-Martian operations focus. A Mars focus offers more opportunity for growing food since more space may be available. A Mars focus also offers a somewhat less harsh radiation environment plus the possible use of regolith for shielding.

A basic and fundamental question came to mind while looking at these options, namely, why is it important for humans to actually be on the surface, especially in light of the expected rich teleoperation and VR environment? With VR technology, the crew will really feel that they are at some remote Martial site even without being there physically.

### C. Earth Transportation Node Location Options

Several node locations were identified and examined in a cursory fashion. The following bullets summarize some key features of each node.

- Low Earth Obit (LEO)
  - Highest delta-V for chemical propulsion
  - Geometry and phasing flexibility
- Earth/Moon Lagrange point (L-1)
  - Lower delta-Vs for escape to Mars
  - Geometry and phasing tied to Moon - OK for Stopover technique
- Low Lunar Orbit (LLO)
  - High delta-Vs for escape to Mars
  - Geometry and phasing tied to Moon - OK for Stopover technique
- High Earth Orbit (HEO)
  - Low delta-Vs for escape to Mars
  - Geometry and phasing flexibility facilitates Escalator orbit technique
- Moon Orbit Radius (MOR)
  - Low delta-Vs for escape to Mars
  - Geometry and phasing flexibility facilitates Escalator orbit technique
  - Energetically close to Lunar resources

Considerable past work (Ref. 3, 4) has characterized optimum spaceport locations, in terms of delta-V requirements, given a set of assumptions. Options for a Mars transportation architecture include LEO, L-1, Moon orbit radius (MOR) [free of Moon's gravity] or even LLO. What is optimum depends on assumptions, especially on existing infrastructure. With a resonant (Escalator) orbit transportation architecture, the LEO and MOR departure nodes provide the most flexibility for reaching the pre-positioned Human Interplanetary Transport vehicle on an Escalator orbit. A Taxi departs a pre-positioned (in longitude) Earth Spaceport in MOR since its location can be optimized in advance to provide the proper phasing for reaching the desired departure asymptote. Since LLO and L-1 are tied to the position of the Moon in its 28-day orbit, a node located at either means that the Taxi is almost never in the optimum point for reaching the desired hyperbolic asymptote. More importantly, if a crew departs on a Human Interplanetary Transport, orbit phasing, which can increase flight time, can be used to minimize any delta-V penalty when launching from the vicinity of the Moon. Long phasing orbits are not practical with a Taxi vehicle since it is not expected to have extensive shielding nor power and consumables on board.

Another consideration is the node proximity (energy-wise) to propellant resources when used. If there is extensive use of Lunar oxygen or water, a location nearby, in terms of energy, is attractive. Here L-1, LLO or MOR all make sense. Since we have focused on an eventual resonant orbit transportation architecture, we assumed the use of MOR as the transportation node since it can easily be moved with very low delta-V and is energetically close to the Moon.

### D. Electric Propulsion Options

There are two options that should be studied further in the future. These include the use of a Hall-thruster, Lunar Cargo vehicle-based stage for taking Cargo Interplanetary Transports out of Earth orbit. Another is the trade-off between one large CIT versus three smaller CITs, that depart at the same time, during the early infrastructure buildup.

**Hall Stage.** A high-thrust, Hall-powered stage, based on the Lunar Cargo vehicle, could reduce CIT spiral time by a significant amount (factors of two to four). This would result in more time available for refurbishment and reloading of CITs after their return to Earth. The use of a high-thrust stage would also reduce radiation damage to the CIT and its cargo caused by spending long periods within the Earth's trapped radiation belts. It is desirable that the Hall stage be able to return to LEO after boosting a CIT out from LEO. The use of a Hall stage would require a re-optimization of CIT power level and thruster size.

**Number of Cargo Vehicles and their Modularity.** There is a trade off of the use of one large CIT versus three smaller CITs for Mars cargo transport. In the buildup of infrastructure at Mars, where large amounts of propellant and hardware are being transported, large cargos and large CITs are required. Once sustained operations are reached, however, much smaller cargo loads are required that require smaller CITs (lower power, fewer or smaller thrusters). Several smaller CITs were examined in the infrastructure buildup so that when sustained operations are reached, the same size CIT vehicle is sufficient.

## V. Bridging Mars Transportation Architecture

This architecture initiates two Human Interplanetary Transports (HITs) onto Escalator orbits between Earth and Mars. One orbit, dubbed the Up Escalator Orbit (UEO), provides short, 5-month trips to Mars. The other orbit, dubbed the Down Escalator Orbit (DEO), provides 5-month trips back to Earth. In this section we summarize the key elements of this architecture, describe the needed infrastructure, and illustrate its CONOPS profile.

### A. Key Elements of the Bridging Architecture

The following list summarizes the key elements of the bridging Mars transportation architecture.

1. Preposition HIT with spare Taxi vehicles into both Up and Down Escalator orbits
   - SEP cargo vehicle (1.3 MW) delivery
   - Emplacement of both prior to Crew-1 departure from Earth
2. Preposition Mars base and Phobos infrastructure via CITs (1-3 MW depending on number of vehicles)
   - Cargo includes Mars Spaceport (HIT heritage), two Human Mars Landers, two Cargo Mars Landers, initial propellant for Crew-1, Mars Base infrastructure, Fuel Depot for Phobos, etc.
   - Two large vehicles or six smaller vehicles sized for sustained operations.
3. Crews depart from Earth and Mars via taxis on hyperbolic trajectories for rendezvous with HITs during flyby.
4. Crew-1 takes about 1 year establishing Mars and Phobos infrastructure and validates Human Mars Lander operation from Mars Spaceport at Phobos.
5. If all is well, Crew-1 visits the Mars Base for ~1 year.
6. Crew-2 arrives and goes to Mars Base soon thereafter.
7. Continual CIT re-supply of Mars and Escalator orbit HITs.
8. Crews transition from 2.9-year tours to 5.1 years (4.2 years at Mars Base).

### B. Needed Infrastructure

The needed infrastructure for this architecture is listed below:

**Earth/Moon**

- Earth Spaceport at Moon Orbit Radius (MOR)
- Propellant depot at Earth Spaceport
- Spare Taxi located at Earth Spaceport
- Two (3 MW) or six (1 MW) LEO-based CITs for transport of cargo to Mars
- Two (0.3-1.3 MW) LEO-based CITs for transport of cargo to HITs
- Lunar Water Production Facility

**Mars/Phobos**

- Mars Base
- Water Production Facility at Mars Base
- Mars Spaceport located near Phobos
- Propellant depot at the Mars Spaceport
- Spare Taxi at the Mars Spaceport
- Phobos Oxygen Production Facility
- Two Human Mars Landers (one spare)
- Two Cargo Mars Landers (will transport hydrogen to Mars Spaceport)

**Escalator Orbits**

- HIT on each of the Up and Down orbits
- Spare Taxi vehicle at each HIT

### C. Concept of Operations (CONOPS) Profile

Figure 7 illustrates the CONOPS profile for example years 2040 through 2058. Because it would be too complex and confusing to have all the transportation elements shown overlaid on the Earth and Mars orbits, we have chosen to display these vehicles as they travel to and from Mars overlaid on several Earth and Mars orbits shown as horizontal lines (Earth – green dashed line and Mars – red dashed line). The tick marks on the vertical axis are 1 Astronomical Unit (AU). Mars is shown at its average of 1.52 AU from the sun or 0.52 AU from Earth. Detail orbit data really corresponded to dates from 2010 to 2028, however, we added 30 years to each date that will result in almost the same planetary geometry and resulting delta-Vs. The top two, red Sine-wave-like lines illustrate the motion of the Up (top) and Down (bottom) Escalators as they flyby Earth and Mars for more than 15 years of operation.

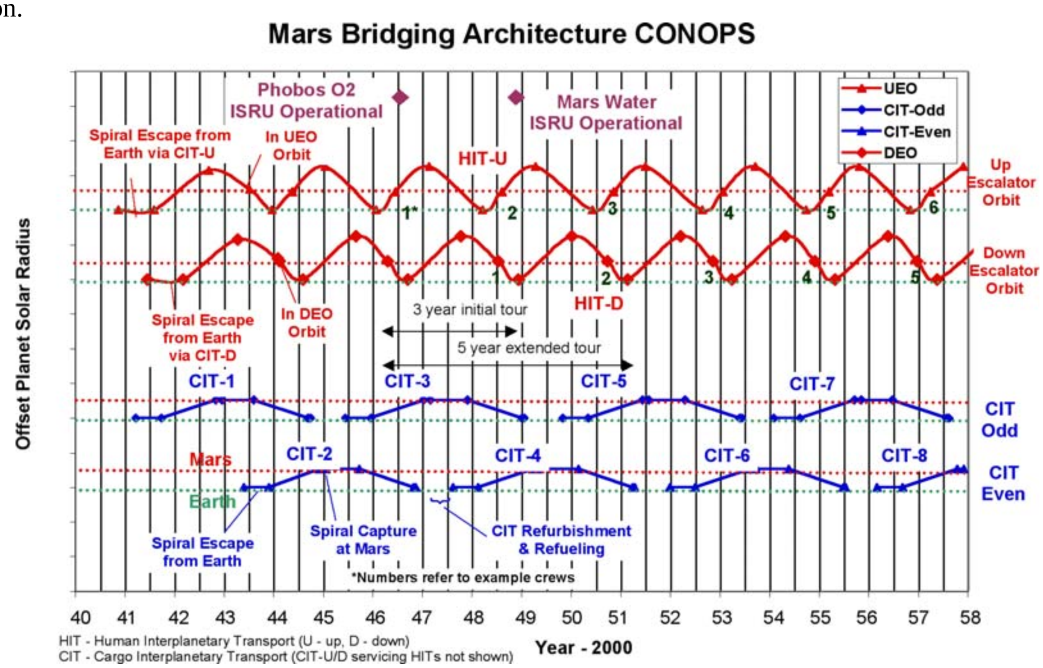


**Figure 7 Mars bridging transportation architecture CONOPS Profile**

The dark green numerals adjacent to the Escalator orbits refer to crew transfers going to or coming from Mars. Crews only occupy the HITs during the short flight durations (~5 months) between the planets. The bottom two sets of lines illustrate the CITs that initially buildup the Mars infrastructure and then sustain it.

In this architecture, the HITs are mated to 1.3 MW SEP CITs for transfer to their eventual Escalator orbits. Spiral departure requires about 265 days followed by over 270 days of powered SEP thrusting. About 670 days from Earth, a 30 day powered thrust phase brings the CIT/HIT combination into the Escalator orbit (see in Figure 7 for the points in each transfer where UEO or DEO orbits are achieved). After leaving the HIT in the proper orbit, the CIT returns to Earth, which requires about 300 days. HITs must carry out periodic and autonomous orbit corrections using their onboard SEP systems. Most thrusting occurs during times when crews are absent from the HIT. The Up Escalator HIT is placed into its orbit one full opportunity before it is to be used by a crew. The Down Escalator HIT is placed into its orbit two full opportunities before its use. This is to ensure that the Down Escalator HIT is in place and operating properly before the first crew departs for Mars. Onboard each HIT is a small SEP system (150kW, 5,000s specific impulse) to execute the periodic trim delta-Vs to keep the orbit in a continuous cycle between Earth and Mars.

In the meantime, CITs begin spiraling out from Earth (LEO) with their Mars-bound cargos. Each CIT requires about 190 days for Earth spiral departure, about 400 days of interplanetary flight, of which about 200 are thrusting, and about 50 days of spiral capture at Mars into a Phobos orbit. Once at Phobos, they will unload cargo robotically and return to Earth. Without cargo the spiral departure is less than one day followed by 400 days of interplanetary flight to Earth. Spiral capture at Earth (to LEO) only takes about 17 days. One CIT leaves at every opportunity requiring at least two CITs. Each CIT has about 230-290 days of time between reflight that can be used for refurbishment, refilling and cargo loading.

Before crew departure from Earth there will already be considerable infrastructure in place at Mars including:

- Mars Spaceport
- Cargo Mars Landers (2)
- Human Mars Landers (2)
- Phobos and Mars ISRU Systems
- Taxi (spare) and Augmentation Tanks
- Consumables (4-years – closed-loop ECLSS)
- Repair Refurbishment, and Upgrade (RRU) hardware
- Propellants

In addition there will be considerable Mars Base hardware in place at Phobos including:

- Habitat (1)
- Washdown Facility (2)
- Power Generation, Storage and Management (2 each 120 kW sets)
- Crane and Trailer
- Base and Mobile Laboratories
- Teleoperated Robots (5)

The first crew (Crew-1) departs Earth via a Taxi (CM/SEM-based with aerocapture capability) from the Earth Spaceport located in an orbit similar to the Moon's at Moon Orbit Radius (MOR). The Taxi executes a small burn (200-1000 m/s) to reduce the perigee of its orbit and to provide the proper phasing between the hyperbolic flyby of the HIT and the Taxi. The flight toward Earth can require several days depending on the time of launch within the launch period, which itself could be several days. A midcourse delta-V may be required between zero and 900 m/s for a total delta-V between MOR and perigee of 1000-1100 m/s. A perigee delta-V of about 1500 m/s (January 2046 opportunity) is required to inject the Taxi on its hyperbolic transfer toward the Up Escalator orbit HIT. The Taxi arrives at the HIT about 5 days later at which time it carries out a small rendezvous delta-V (<20 m/s) and then docks with the HIT. The crew then enters the HIT for its 5-month trip to Mars. A few days (~5-7) before arriving at Mars the crew enters a Taxi (one of two that are docked) and departs the HIT with a small deflection delta-V that targets the Taxi for atmospheric entry and aerocapture. Reaching Mars, the Taxi enters the atmosphere and begins an aerocapture maneuver, which is characterized by descent to about 45 km altitude, constant altitude, bank-modulated, aerocruise to deplete speed, and ascent and escape from the atmosphere with sufficient energy to ascend to the Phobos orbit. Once at Phobos Orbit Radius (POR), the Taxi executes a small delta-V (700-800 m/s) to circularize its orbit. It then docks with the Mars Spaceport that has been pre-positioned in orbit near Phobos.

Two each Mars Cargo and Human Landers will be pre-positioned at the Mars Spaceport. The Cargo Landers (payload to Mars surface of about 20-30 mt) will have the capability for trips to and from the Martian surface to deliver cargo for setting up a base. The Cargo Mars Lander also has the ability to return about 5 mt of cargo to

Phobos, which could be liquid hydrogen produced at the Mars Base if water is not available at Phobos. The Human Mars Lander (with a 10 mt cargo capability) will be able to be refueled on Mars, using previously emplaced or produced propellants for return to Phobos.

In this architecture the first crew spends its first 10 months at the Mars Spaceport (which utilizes artificial gravity) teleoperating cargo lander unloading operations on the surface of Mars. In addition, Crew-1 will build the Phobos infrastructure especially the Phobos Oxygen Production Facility that should be operational at this time. Because there is little light-time delay, as compared to even Earth's Moon from the Earth, Crew-1 can begin teleoperating robots involved in the siting, constructing and operating key elements of the Base infrastructure and water production facilities. The Human Mars Lander can be launched, uncrewed, from Phobos, and be landed at the Mars Base location and off-load cargo. Afterward, it could be refueled and launched back to Phobos. This operation provides a good validation of both entry and launch capabilities and performance before it is ever crewed.

After being assured that all infrastructure is in place for the first visit to the Martian surface, the crew enters the Human Mars Lander (HML), docked at the Mars Spaceport, and executes a single delta-V that targets the lander to direct entry near the Mars Base. This first crew spends about 14 months on the surface of Mars exploring and monitoring the setting up of newly arrived hardware and supplies. Just before the first crew travels to the Mars Base the third CIT arrives at Phobos. Although the Mars Water Production Facility is expected to be operating at this time, it is not assumed operational until the second crew arrives. At the end of its Martian surface visit the crew enters the HML, which has been refueled by pre-positioned propellants, and returns to the Mars Spaceport. Upon arrival, the crew spends the next two months preparing to depart Mars. The crew oversees the refueling (from pre-positioned propellants) of the Taxi, which, for this opportunity will not require additional augmentation tanks. A few hours before the Down Escalator HIT arrives at Mars periapsis, the Taxi departs the Mars Spaceport headed toward a 200 km periapsis where it will execute a large delta-V to place it onto a hyperbolic rendezvous trajectory with the HIT. About 5 days later, the Taxi does a small delta-V to rendezvous with the HIT.

Once docked, the crew exits the Taxi and enters the HIT where they will spend the next 5 months on their way back to Earth. During this time they will oversee the repair, refurbishment, and upgrade of HIT hardware and carry out the stowage of cargo that has arrived via the small CITs dedicated to HIT resupply. These small CITs resupply each HIT every other opportunity. A few days out from Earth the crew prepares to leave the HIT. They enter a Taxi and execute a small deflection maneuver targeting the Taxi to an Earth aerocapture maneuver. This aerocapture maneuver could place the Taxi in a near LEO orbit or onto an elliptical trajectory to the Earth Spaceport in MOR where the Taxi orbit is circularized.

A few months after Crew-1 departed Mars, Crew-2 arrives at Mars via the Up Escalator HIT. In this architecture, crew tours could start at about 3 years, which would mean only 10 crew at a time at the Mars Base and no overlap between crews. After sufficient experience has been gained with the Martian gravity and environment, crew tours could be extended to 5 years. A 5-year tour would enable almost 20 crew continuously at the base, each having almost 4 years on the surface.

### D. Mars Infrastructure Buildup

The following tables describe the cargo manifests for the CITs supporting Mars. Table 3 shows the buildup of the Mars Base infrastructure as a function of CIT and its arrival date. Table 4 shows the buildup of other important infrastructure at Mars by the same CITs.

## VI. Results

The following tables and discussion reviews the results of the bridging CONOPS in terms of pre-deployed hardware, required size of cargo vehicles, and crew times.

### A. Infrastructure and Logistics Buildup

The following table compares the buildup of the Mars infrastructure before the first crew departs Earth. The Mars Base centered CONOPS has over 90 mt more of infrastructure delivered before the first crew departs Earth. This high level of pre-deployed material shows that we will be well prepared and have high confidence in success before the first crew's journey begins.

**Table 3 Mars Base Buildup**

| Mars Base Systems | # of Units | Unit Mass, mt | Total Mass, mt | CIT-1 | CIT-2 | CIT-3 | CIT-4 | CIT-5 | CIT-6 | CIT-7 | CIT-8 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cargo Payloads, mt ---> | | | | 166.6 | 166.2 | 166.3 | 166.3 | 162.8 | 48.3 | 38.2 | 38.2 |
| Arrival Date ---> | | | | 11-Dec-42 | 11-Jan-45 | 20-Feb-47 | 4-May-49 | 20-Jul-51 | 18-Sep-53 | 30-Oct-55 | 8-Dec-57 |
| **Life Critical Systems** | | | | | | | | | | | |
| Habitat | 4 | 38.5 | 154.0 | | 1 | | | 3 | | | |
| Washdown facility | 2 | 0.9 | 1.8 | | 2 | | | | | | |
| Life Critical Systems Subtotal | | | 155.8 | | | | | | | | |
| **Mission Support Systems** | | | | | | | | | | | |
| 120 kW Power Source (solar array @100W/kg) | 2 | 1.2 | 2.4 | 1 | 1 | | | | | | |
| Power Management, Distribution and Maintenance | 2 | 0.3 | 0.6 | 1 | 1 | | | | | | |
| Energy Storage (NRFC packages) | 2 | 1.0 | 2.1 | 1 | 1 | | | | | | |
| Suitup/Maintenance Facility | 2 | 1.8 | 3.6 | | | 1 | 1 | | | | |
| Pressurized Rover | 3 | 9.1 | 27.3 | | | | 2 | | 1 | | |
| Open Rovers | 3 | 1.0 | 3.0 | | | 1 | 2 | | | | |
| Inflatable Shelter w/Airlock | 10 | 0.5 | 5.0 | | | 5 | 5 | | | | |
| Crane | 2 | 5.0 | 10.0 | | 1 | | 1 | | | | |
| Trailer | 2 | 2.0 | 4.0 | | 1 | | 1 | | | | |
| Mission Support Systems Subtotal | | | 58.0 | | | | | | | | |
| **Science and Exploration Systems** | | | | | | | | | | | |
| Base Laboratory | 2 | 13.6 | 27.2 | | 1 | | | | 1 | | |
| Mobile Laboratory | 3 | 9.1 | 27.3 | | 1 | 1 | | 1 | | | |
| 200 m Drill | 1 | 2.3 | 2.3 | | | 1 | | | | | |
| 10 m Drill | 3 | 0.1 | 0.3 | | | 1 | 2 | | | | |
| UAV | 3 | 0.3 | 0.9 | | | 1 | 2 | | | | |
| Teleoperated Robots | 10 | 0.2 | 2.0 | | 5 | | 5 | | | | |
| Weather Station | 5 | 0.2 | 1.0 | | | 5 | 5 | | | | |
| Science and Exploration Systems Subtotal | | | 61.0 | | | | | | | | |
| **Total Base** | | | **274.8** | | | | | | | | |

**Table 4 Other Mars Infrastructure**

| Other Mars Infrastructure | # of Units | Unit Mass, mt | Total Mass, mt | CIT-1 | CIT-2 | CIT-3 | CIT-4 | CIT-5 | CIT-6 | CIT-7 | CIT-8 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cargo Mars Landers | 2 | 13.0 | 26.0 | 1 | 1 | | | | | | |
| Human Mars Landers | 2 | 17.0 | 34.0 | 1 | 1 | | | | | | |
| Phobos Oxygen Production Facility | 1 | 10.0 | 10.0 | 1 | | | | | | | |
| Mars Spaceport (with artifical g) | 1 | 60.0 | 60.0 | 1 | | | | | | | |
| Mars Water Production Facility | 1 | 5.0 | 5.0 | | 1 | | | | | | |
| Phobos Propellant Storage Depot | 1 | 2.0 | 2.0 | 1 | | | | | | | |
| Taxi (Spare) | 1 | 16.0 | 16.0 | | 1 | | | | | | |
| Taxi Augmentation Tanks | 10 | 6.6 | 66.0 | | 1 | 2 | | 2 | 1 | 2 | 2 |
| Consumables, mt | | | 139.0 | 15.0 | 15.0 | 15.0 | 20.0 | 20.0 | 14.0 | 20.0 | 20.0 |
| Repair, refurbishment & Upgrade Hardware, mt | | | 40.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| Propellants, mt | | | 279.0 | 42.0 | 15.0 | 115.0 | 107.0 | | | | |
| **Total Other** | | | **677.0** | | | | | | | | |

**Table 5 Infrastructure and Logistics Buildup Prior to Crew-1 Departure from Earth**

| Infrastructure and Logistics (CIT-1 & 2) | Bridging Architecture, mt |
|---|---|
| Mars Base | 76.1 |
| Other Infrastructure | 159.6 |
| Cycling Vehicles | 120.0 |
| Subtotal Infrastructure | 355.7 |
| Consumables | 30.0 |
| Repair, Refurbishment & Upgrade H/W | 10.0 |
| Propellants | 57.0 |
| Subtotal Logistics | 97.0 |

### B. Cargo Interplanetary Transport

In the following table one can see that the maximum cargo size during infrastructure buildup is about 167 mt. This results in a SEP system power level that is 2.1 MW larger and a CIT that is 8 mt larger (at 4 kg/kW) than needed in the sustaining architecture.

**Table 6 Cargo Interplanetary Transport**

| Mars Cargo Interplanetary Transports | Bridging Architecture |
|---|---|
| ***Buildup*** | |
| Maximum Payload, mt | 166.6 |
| Power Level, MW | 2.9 |
| Total Mass Delivered (8 trips) | 677.0 |
| ***Sustaining*** | |
| Payload, mt | 38.2 |
| Power Level, MW | 0.84 |

### C. Crew Time

The following chart lists crew times (total tour, time on Mars surface, and space flight time) for the Mars bridging transportation architecture. We show both the minimum time and the times for sustained operations where crews would actually overlap.

**Table 7. Crew tours of duty**

| Crew Times | Bridging Architecture |
|---|---|
| ***Total Crew Tour*** | |
| Minimum, years | 2.9 |
| Sustained, years | 5.1 |
| ***Crew Mars Surface Tour*** | |
| Minimum, years | 2.1 |
| Sustained, years | 4.3 |
| ***Crew Flight Time*** | |
| Earth to Mars, days | 150 |
| Mars to Earth, days | 150 |

## VII. Robotic Precursor Missions

Several robotic precursor missions were identified that would provide key information for further architecture development. These include:

- Lunar South Pole Lander/Hopper
- Lunar ISRU Experiments
- Phobos Orbiter-Lander
- Phobos IRSU Experiments
- Mars Surface ISRU Experiment Lander

In the following sections we briefly list the instruments/experiments that could be considered for these robotic precursor missions and we briefly describe a typical mission scenario.

### A. Lunar Lander/Hopper

- Rover for sample collection and site survey
- Gamma ray or Neutron Spectrometer for hydrogen detection and bulk abundance measurement
- Drill (>2 m)
- Oven(s) with evolved gas analyzer(s)
- Subsurface Sounding Radar
- Visible/IR Imagers
- Laser-induced breakdown spectroscopy (LIBS) for remote surface composition analysis

Mission Profile: Land at multiple sites (2-3) making measurements and doing site surveys if measurements are promising.

### B. Lunar ISRU Experiments

Assuming water is found *in-situ*, Water Excavator/Extractor Experiment Lander

- Mini processing facility (separator, oven, condenser, storage)
- Video imagers
- Rover lunar regolith excavator experiment(s)

### C. Phobos Orbiter-Multi-Lander

Russia currently is planning an ambitious sample return mission to Phobos in 2012 called Phobos-Grunt. The Phobos-Grunt mission will carry several instruments including:

- TV system for navigation and guidance
- Soil sample collection system
- Gamma ray spectrometer
- Neutron spectrometer
- Alpha X spectrometer
- Mass spectrometer
- Seismometer
- Long-wave radar
- Visual and near-infrared spectrometer
- Dust counter
- Ion spectrometer
- Optical solar sensor

Mission Profile: Flight to Mars will take about 10 months. After spending several months exploring Mars and Phobos and Deimos from orbit, it will land on Phobos. Arrival is in October 2012 and landing in February 2013. Upon landing, the soil sample collection will begin collecting samples. Shortly after samples have been collected, the sample return rocket fires to bring the samples back to Earth, where it is expected to arrive in August 2014. The lander continues its experiments for a year (Ref. 5).

### D. Phobos IRSU Experiments

Water found - Water Excavator/Extractor Experiment Lander

- Mini processing facility (separator, oven, condenser, storage)
- Video imagers
- Rover lunar regolith excavator experiment(s)

No Water - Oxygen Extraction Experiment Lander

- Mini carbothermal reduction facility (reactor, gas processor, O2 liquefaction)
- Video imagers
- Rover regolith excavator experiment(s)

### E. Mars Surface ISRU Experiment Lander

Mars Surface Regolith Excavation, Water Extraction, LOX/LH Production Experiment Lander

- Regolith excavator experiment(s)
- Oven
- Condenser
- Water storage
- Video imagers

## VIII. Technology Needs

In this section we describe the resultant technology needs for this bridging and sustained Mars exploration transportation architecture.

### A. Aerocapture Systems

Two aerocapture technology needs are called for in this architecture including moderate lift-to-drag ratio (L/D) aeroshells and deployable, low L/D aeroshells.

**Moderate L/D Aeroshells.** Aerocapture provides for an efficient and reliable planetary capture capability. One can argue that aerocapture is more reliable since fewer onboard systems need to function during the aerocapture maneuver than when propulsion systems are used. Moderate L/D (~0.7) aerocapture systems are required for Taxi capture at Earth and Mars (entry speeds up to 12.5 km/s). Bank modulated lift will be needed. Aeroshell design should offer significant flexibility for locating crew modules and propulsion systems behind it. This technology will result in significant savings in propellant requirements for the initial buildup and reduce the size of ISRU systems. Target system mass is 15% of entry vehicle mass.

**Deployable, Low L/D Aeroshells.** A deployable and restowable, or disposable, low L/D aeroshell is needed for Human and Cargo Mars Landers on direct entry trajectories from Phobos orbit. This could be a simple Viking aeroshell (70° cone angle) design that has considerable heritage at Mars. The Viking shape provides a flexible payload placement with large volume and Cg location. A Viking design also produces a less complex transition from entry to landing than slender bodies (e.g. sled). Target system mass is 15% of entry vehicle mass.

### B. Electric Propulsion Systems

High-power (0.3-4.4 MW AM0), high-specific impulse (5,000 to 10,000 s) for Cargo Interplanetary Transport (CIT) vehicles are required to keep propellant masses low. Combined specific mass of 8 kg/kW is required to keep propulsion system mass low.

### C. High-thrust Propulsion

Higher thrust LOX/LH engines (~267 kN) will be required to reduce gravity losses. Extended nozzles are attractive to produce compact systems within aeroshells. Mixture ratios of 7:1 will reduce the volume of LH tanks and have little negative performance impact.

### D. In-Situ Resource Utilization (ISRU) Systems

*In-situ* resource utilization (ISRU) systems at the Moon, Mars and on Phobos will significantly reduce mass in LEO for sustained operations. ISRU systems will result in lower life cycle costs if launch costs are higher than about $1k/kg.

## IX. Recommendations

There are several preliminary recommendations regarding a Mars concept of operations. These include 1) the need for robotic precursors to establish the nature of *in-situ* resources and demonstrate extraction techniques at the Moon, Mars and Phobos; 2) a resonant orbit transportation architecture should be developed utilizing the low-thrust vehicles on Escalator orbits; 3) significant infrastructure and logistics should be transported to Mars prior to the first crew departure from Earth; 4) the location of Earth transport node should be at Moon Orbit Radius (MOR) to provide maximum orbit phasing flexibility and proximity (energetically) to Lunar resources; 5) the location of the Mars transportation node should be near Phobos to be close to resources and to reduce Mars lander entry requirements; 6) there should be significant reliance on teleoperation of robots on the surface of Mars from the vicinity of Phobos for initial Mars Base set up, monitoring and validation, 7) the use of aerocapture systems should be maximized for reliable and efficient planetary capture of crewed vehicles; 8) the transport of cargo should be via electric propulsion vehicles; 9) Spaceports should be located at Earth and Mars transport nodes to offer crew transition to interplanetary vehicles and to provide safe-haven options.

## X. Conclusion

A pair of synergistic exploration architectures have been discussed, one for Lunar exploration and one for Mars exploration, following a Moon first, then Mars exploration strategy. The Lunar exploration architecture consists of an all chemical propulsion system requiring two launches to place four humans on the surface of the Moon, and a main Lunar Base for all Lunar operations. The Mars exploration architecture can transport ten humans at a time to the surface of Mars, once the architecture is in place, and features a main Mars Base as the focus of Martian operations. Both architectures rely on major pre-positioned assets to be in place and functional before the first human explorers arrive. Both architectures have a self-sustained CONOPS as the end goal. Both architectures manufacture propellant *in-situ* as much as possible, rather than transporting all propellants from Earth. The bridging CONOPS from the Lunar exploration architecture to the Mars exploration architecture has been developed in detail..

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## References

[1]Orbital Sciences Corporation, Preliminary Concepts for Human Lunar Exploration and Crew Exploration Vehicle: Option Period Final Report, Contract No. NNT04AA02C, September 9, 2005.

[2]Kosmann, William J., Bocam, Kenneth J., "A Recommended Lunar Exploration Architecture", *57th Congress of the International Astronautical Federatio*n, IAC-06-D3.3.02, pp. 1-15, (2006), International Astronautical Federation, Paris, France.

[3]Nock, K. T., Cyclical Visits to Mars via Astronaut Hotels, Phase II Final Report, Global Aerospace Corporation, Universities Space Research Association Subcontract No.: 07600-59, GAC Report 510-05921-023, April 9, 2003.

[4]Nock, K.T., An Express Transportation Architecture for Human Mars Exploration, AIAA Paper, Space 2011 Conference, September 2011.

[5]See http://en.wikipedia.org/wiki/Fobos-Grunt#Instruments, accessed September 1, 2011.