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An Express Transportation Architecture for Human Mars Exploration

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If future plans for human space travel include recurring visits to a Mars Base for research and exploration, an efficient and fast transportation system will be crucial for rotating crews back and forth between Earth and Mars and to resupply needed equipment and fuels. An innovative interplanetary transportation architecture is described that uses highly autonomous, solar-powered, ion-propelled Astronaut Hotels, dubbed Astrotels; small Taxis for trips between Astrotels and planetary Spaceports; Shuttles that transport crews to and from orbital space stations and planetary surfaces; and ion-propelled low-thrust freighters that deliver cargo to Astrotels and Spaceports. Astrotels and Taxis enable transportation of replacement crews, on short, frequent trips between Earth and Mars. Astrotels orbit the Sun with periodic flybys of Earth and Mars, while Taxis fly between Astrotels and planetary Spaceports. Two crews work on Mars with alternating periods of duty, each spending about 4 years there with crew transfers occurring about every two years. Also discussed are the production of rocket fuels using materials mined from the surfaces of the Moon, Mars and the Martian satellites; the use of aerocapture to slow Taxis at the planets; and finally, the estimated total life-cycle cost of this interplanetary transportation architecture.

I. Introduction

Currently, there is a national dialogue on where the US should take human spaceflight in the future; Mars, an asteroid or the Moon. Some think that a near Earth asteroid (NEA) should be the next target because it may be easier to travel to than Mars or the Moon and because NEAs could be a source of extraterrestrial resources. Others believe that the Moon represents a unique scientific observation base and a source of water, which can be converted to rocket fuel, to facilitate space exploration. Of these targets, only Mars represents another planet and one on which we, as human beings, could find similarities with our home planet. Mars has an atmosphere with seasons, clouds, fog, frost, and wind; a 24.7-hour day and a significant gravity level; a surface with volcanoes, sand dunes, and canyons; available water; and the equivalent surface area of our own planet's land mass. Temperatures can be a cold -225°F at the winter poles but 80°F on the soil in the summer; closer to Earth temperatures than an asteroid or the Moon. Airplanes and balloons can fly in the Martian atmosphere. Life could have existed in the past on Mars and it could exist today if protected below the surface.

In addition to being more habitable than alternative destinations, Mars also offers the opportunity for scientists to directly explore a neighbor planet and to test theories of solar system and planet formation. So Mars could be a good choice for future human exploration beyond Earth. However, if Mars is a good choice and frequent trips mounted, transportation needs to be affordable or else, after one or two trips, political support fades due to the high cost and we abandon Mars exploration like the US did with the Moon in the 1970s. In order to make future Mars exploration affordable, the US needs to avoid unnecessary and expensive technology developments and take advantage of one of the cheapest and most useful extraterrestrial resources: water. In order to make a Mars transportation system affordable it may require development of lunar and/or asteroidal resources. In this fashion, these bodies are not an ultimate exploration goal, but stepping stones to Mars.

The interplanetary orbital technology and transportation systems architecture that is discussed is affordable, extensible, and could have a potential role to play in the development and implementation of an expedition phase of Mars exploration. Key features of this express transportation architecture are the 1) use of resonant orbit technology and multiple crew transport vehicles to reduce crew trip time to about 5 months; 2) specialization of transport vehicles for crew or cargo and for interplanetary, aerocapture and space-to-surface operations to simplify

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requirements and keep costs low; 3) modular transportation elements to increase commonality and reduce development and operations costs; 4) mining and processing of extraterrestrial water to make and store rocket propellants; 5) planetary transportation nodes located “energetically” near water resources; 6) application of aerocapture to place transport vehicles into planetary orbit without propulsion; and 7) efficient, low-thrust vehicles for transporting cargo from Earth.

This architecture, which is the result of work funded by the NASA Institute of Advanced Concepts (NIAC) (Ref 1) uses highly autonomous, solar-powered, xenon ion-propelled Astronaut Hotels, dubbed Astrotels; small aerocapture-capable Taxi vehicles for trips between Astrotels and planetary Spaceports; 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 orbits; one each for the 5 month trip to Mars and for the 5 month trip return to Earth. These Astrotels and Taxis enable transportation of 10-person replacement crews between Earth and Mars. It is because of the short, 5 month trip to and from Mars that we label this transportation architecture *express*. Astrotels continuously loop around the Sun in resonant 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 1 is a sketch that illustrates the overall architecture of sustained Mars transportation operations for the 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 1 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.

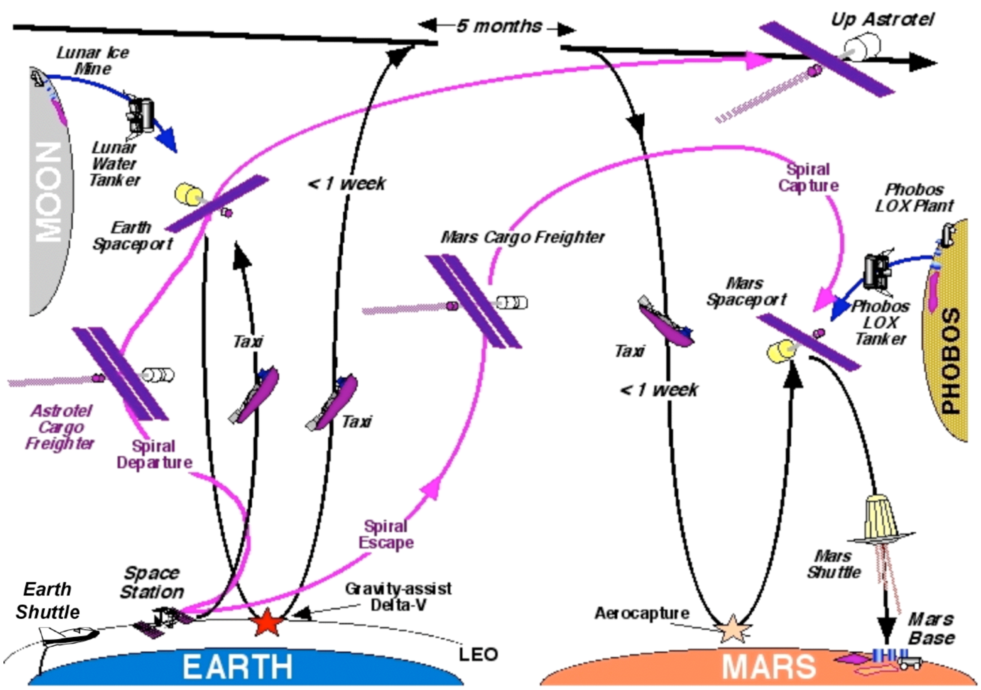


Figure 1. Overall concept of operations for the Earth to Mars flight profile.

Figure 2 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.

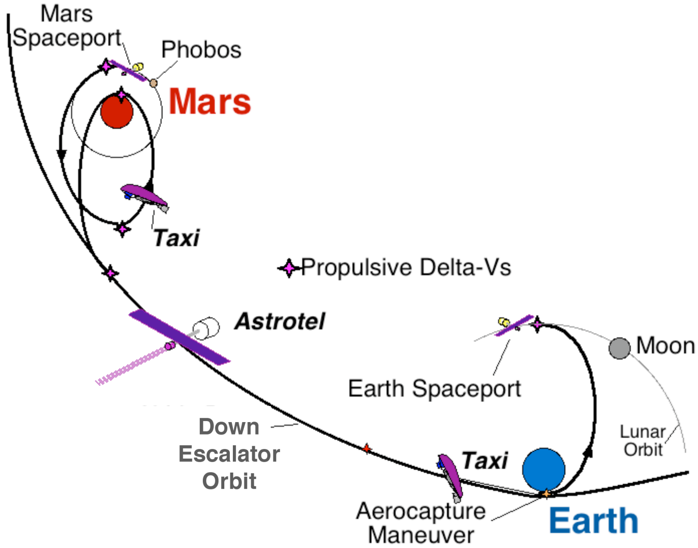


Figure 2. Overview of crew transport from Mars to earth.

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.

Human exploration could benefit from a focus on future permanent Mars habitation, instead of brief and expensive expeditions. Embracing a sustained transportation architecture early in an expedition phase means that permanent Mars inhabitation will progress more rapidly, with better-defined technology goals, and with lower development and life-cycle costs. In this way the architecture drives technology rather than the technology driving the architecture. An implication of pursuing this path toward a Mars transportation architecture is near-term development of intermediate systems of immediate benefit to human space exploration, which can play a part in the expedition phase of human Mars exploration. The inevitability of human Mars exploration will be much closer once we begin taking these steps.

II. A Mars Base

Before creating an Earth-Mars transportation system architecture, one must have an idea of how extensive is a Mars Base. For the architecture discussed here, a robust and active Mars Base is envisioned that could provide scientists and explorers accommodations, power, planetary and interplanetary communications, life support, crewed and robotic mobile and stationary laboratories, exploration tools, resource mining and conversion infrastructure, and space launch and landing facilities. The level of Mars Base capability supports significant surface activities in the areas of science exploration, resource surveys, life-cycle maintenance, propellant production, and materials processing and fabrication. These activities take place at one or two fixed-site facilities on Mars and on distant traverses from the base. Such operations require a high degree of mobility, appropriate levels of automation with efficient man-machine interfaces, and they require crews that combine the need for individual specialization with job sharing abilities. A complement of 20 people on the Martian surface, made up of two overlapping 10-person crews, carry out these activities. The resident population, at any time, fluctuates substantially from the average depending on the phase of the crew rotation cycle dictated by the interplanetary transportation orbit opportunities. The Mars surface is continually inhabited, thereby requiring staggered crew rotations and, thus, overlap between "experienced" and "fresh" personnel.

The Mars Base is nearly self-sufficient and it maximizes its use of *in situ* resources with minimal replenishment from Earth. Robotics and automation activities are focused on *in situ* resource, refurbishment, repair and upgrade (RRU), power generation, and life support monitoring functions. The environmental control and life support systems are regenerative to a large degree but not entirely closed. Life support gases and water are extracted from the soil and atmosphere as needed. Agriculture, in greenhouses and aquaculture, supplies plants and perhaps animals for food. Propellants for mobility systems on the surface and in the atmosphere and for rocket transportation between the Mars Base and space are created *in situ*.

The entire Mars Base requires delivery of about 275 metric tonnes (mt) of hardware to the surface in the buildup phase, about 2/3 of the mass of the current International Space Station (ISS), and about 50 mt of RRU hardware every 15 years. Table 1 summarizes the mass of the various base elements. To support the Mars Base a means of transporting crews and RRU equipment between the planets is needed. It is the crew and logistical support to this base that is the driver for the Mars transportation orbital and systems architectures.

Table 1. Mars Base Infrastructure

Mars Base Systems	# of Units	Unit Mass, mt	Total Mass, mt
Life Critical Systems			
Habitat	4	38.5	154.0
Washdown facility	2	0.9	1.8
Life Critical Systems Subtotal			155.8
Mission Support Systems			
120 kW Power Source (solar array @100W/kg)	2	1.2	2.4
Power Management, Distribution and Maintenance	2	0.3	0.6
Energy Storage (NRFC packages)	2	1.0	2.1
Suitup/Maintenance Facility	2	1.8	3.6
Pressurized Rover	3	9.1	27.3
Open Rovers	3	1.0	3.0
Inflatable Shelter w/Airlock	10	0.5	5.0
Crane	2	5.0	10.0
Trailer	2	2.0	4.0
Mission Support Systems Subtotal			58.0
Science and Exploration Systems			
Base Laboratory	2	13.6	27.2
Mobile Laboratory	3	9.1	27.3
200 m Drill	1	2.3	2.3
10 m Drill	3	0.1	0.3
UAV	3	0.3	0.9
Teleoperated Robots	10	0.2	2.0
Weather Station	5	0.2	1.0
Science and Exploration Systems Subtotal			61.0
Total Mars Base			**274.8**

III. Orbit Architecture

The orbit architecture discussed here includes resonant orbits between Earth and Mars, hyperbolic rendezvous trajectories, planetary Spaceport locations, and low-thrust trajectories.

A. Escalator Resonant Orbits

Orbits between Earth and Mars can be designed to enable sustained and repeatable human interplanetary transportation through regular encounters with Earth and Mars. These types of orbits are called resonant because there is a synchronous gravitational relationship between the orbit and the orbits of Earth and Mars that can be expressed as a simple ratio of their orbital periods. Several Earth-Mars resonant orbit concepts have been developed to support studies of sustained Mars operations, however, only one type minimizes the number of transport vehicles and repeat period (Ref. 2, 3, 4). This type of resonant orbit, sometimes called Escalator Orbit, can be seen as viewed from the North Ecliptic Pole in Figure 3.

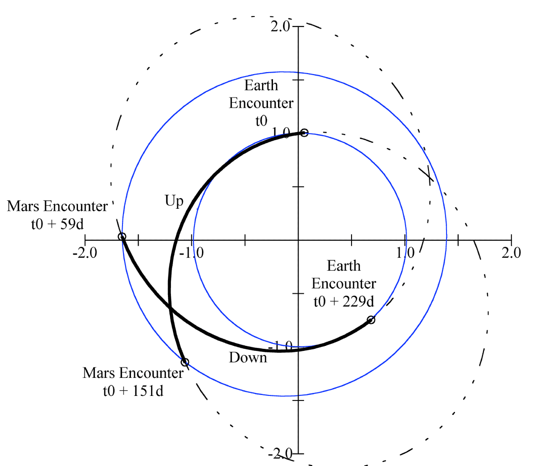


Figure 3 Up and Down Escalator Resonant Orbits

Earth-Mars Escalator resonant orbits have a period that is approximately equal to the Earth-Mars synodic period of 2 1/7 years and, when the line of apsides[†] is rotated by gravity assist at planetary flyby (average of about 51.4° each orbit), enables Earth-to-Mars and Mars-to-Earth transfers every 26 months. Escalator orbits come in two types, an Up Escalator and a Down Escalator orbit. The Up Escalator has the fast transfer occurring on the Earth to Mars leg while the Down Escalator is just the reverse. The term Escalator orbit is derived from that fact that, while one can use a down escalator to go up it is very inefficient and time-consuming to do so. Similarly,

[†] Line connecting the orbit periapsis (closest approach to the sun) and apoapsis (farthest distance from the sun).

one could use any one Escalator orbit for transportation to and from Mars, but it is much more efficient, and safer, to have crews fly only the Escalator orbit that offers the short 5 month transit time between planets. Figure 3 illustrates both orbit transfer geometries. When two Astrotels are used, an Escalator orbit provides relatively short transit times and regular transit opportunities. However, the planetary encounters occur at high relative velocities and typically, impose harsher aerocapture requirements on the Taxi relative to minimum energy, Holman-like trajectories. Also, Escalator orbits require a modest mid-course correction on 3 out of 7 orbits to maintain the proper orbit orientation. These delta-Vs are carried out using low-thrust, solar powered xenon ion propulsion systems (IPS).

Escalator orbits have been selected as the resonant orbit architecture because of several key advantages over conventional minimum energy planetary transfers. Two key advantages are that Astrotels do not require high-thrust propulsion systems and they never stop. The implication of these advantages, combined with the use of low-thrust propulsion systems, is that Astrotel capability can be incrementally increased over time with very little propulsion cost. Example increased capabilities include more radiation shielding, incorporation of artificial gravity if desired, redundancy in the form of additional Taxi and/or escape vehicles, and a growing cache of repair hardware, propellants and consumables at the Astrotel. Finally, by using this Escalator orbit architecture, only two Astrotel vehicles need to be constructed and maintained.

B. Hyperbolic Rendezvous

Escalator orbits with Earth and Mars hyperbolic flybys require transfers between a planetary Spaceport and an Astrotel via a Taxi vehicle. In this orbit architecture, the Earth Spaceport is in a Moon-radius orbit about the Earth, but not necessarily near the Moon. This Spaceport location has significant cost implications since lunar resources are "energetically" very close as will be discussed later. The Astrotel flyby is completely constrained in periapsis date, distance, and inclination, since it must continue to travel on its desired path between the planets. A past concern for the use of Escalator orbits for human transportation has been the need for hyperbolic rendezvous (Ref. 5) where the Taxi must depart the Earth with a near instantaneous launch period without any margin for error or hardware delay. In actuality, an instantaneous launch period is not required. The primary restriction is, however, that the rendezvous must take place within about 10 days from the time of departure from the Spaceport because Taxis have limited consumables and life support and are lightly shielded against radiation. Figure 4 shows the Spaceport orbit, the Astrotel flyby and three Taxi hyperbolic rendezvous options. Having to solve the hyperbolic rendezvous problem provides insight into the desired location of the Earth Spaceport. Plane changes are best made far from the planet where the orbital velocities are low. Velocity changes are best made close to the planet, i.e. within the gravity well. In LEO, the orbital velocity is about 7.5 km/s, whereas at lunar distance, the velocity is about 1 km/s, which is a much more efficient place to make a required plane change.

A 4-burn transfer, illustrated in Figure 4, is used because it enables a built-in launch period of a few days and it requires a low total delta-V and a short flight time. If a Taxi is not ready to launch toward the Astrotel on time, a planetary opportunity will be missed. How do we ensure that the vehicle does not miss the injection? One way is to have an extended launch period measured in days, not minutes or seconds. This could be achieved, depending on orbital alignment, by including Taxi delta-V propellant reserves that allow a slower or faster Spaceport departure to build in a launch period. The first delta-V slows the Taxi allowing it to drop within the Earth's gravity well and provides time phasing. A second delta-V drops the orbit deep within the gravity field. Once at 200 km altitude periapsis, the Taxi carries out the third delta-V, a major burn, that targets the Taxi to an intercept of the hyperbolic Astrotel. The final small delta-V, far from Earth, results in the rendezvous of the Taxi with the Astrotel.

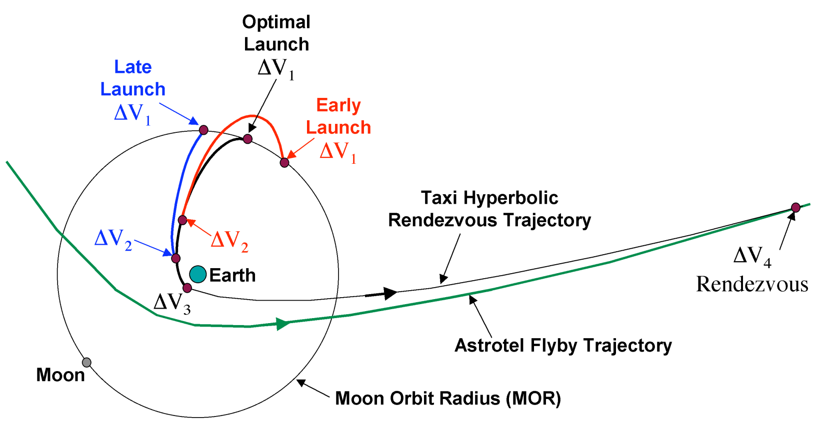


Figure 4 Hyperbolic Rendezvous Schematic (not to scale).

The delta-V at perigee, ΔV_3, needs to be done within minutes of its intended time, however the trajectory from the Earth Spaceport to this critical periapsis could take varying amounts of time thus building in a launch period for the departure from the Spaceport. Building in this launch period means flying non-optimal trajectories from the Spaceport to the periapsis that results in higher than optimal delta-V.

Figure 5 shows the total Taxi delta-V cost as a function of launch time relative to the near-optimal, lowest delta-V time. Near minimum delta-V occurs for a flight time from Spaceport to perigee of about 5 days. One can see that more than eight days of launch period can be created for departure from Spaceport to rendezvous with the Astrotel for an additional reserve of only about 20% (500 m/s) of the minimum delta-V. Almost no additional reserve is required for a launch period of 4 days. This demonstrates the flexibility of the hyperbolic rendezvous approach.

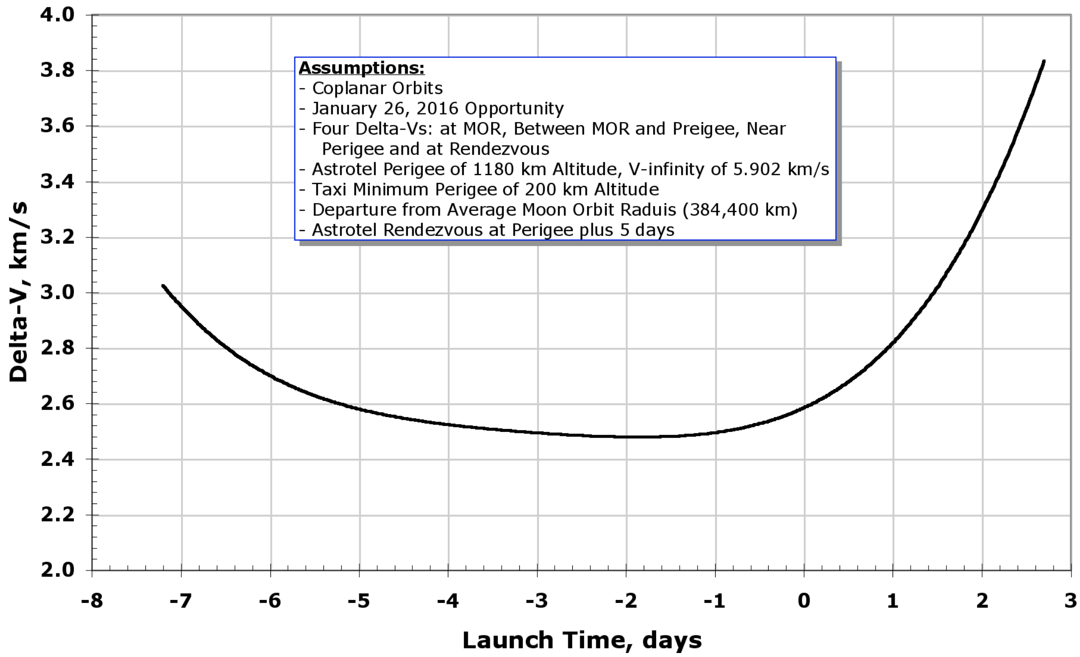


Figure 5 Total Taxi delta-v as a function of launch time from the near-optimal time.

What kinds of things could go wrong that could require a longer launch period? A taxi could have a hardware or software failure. One can mitigate the random hardware or software failure by having more than one Taxi ready for departure. If, during the countdown, one Taxi is found to have a fault that requires more time than the launch period provides, the spare Taxi could be provided and used.

Non-catastrophic engine failures could be dealt with by providing more engines than absolutely required. If an engine fails during a critical burn the remaining engines continue to fire until the desired orbit energy is achieved. For a delta-V near periapsis, this may result in delta-V losses coming from the fact that the burn is now carried out over a larger range of altitude (gravity losses). The way to mitigate this potential loss is to carry propellant reserves to allow for a one or two engine out scenario.

Finally, what happens when, during a critical burn, there is a complete system outage that results in partial burn of injection delta-V? If this were to occur on any burn except the perigee burn there would be time to recover. If such an event occurred at the start of the perigee burn, the Taxi would still be in Earth orbit. Were this to occur in the middle of this critical perigee burn and systems could not be rebooted immediately, the Taxi could be on a hyperbolic path to nowhere and the crew could be lost. Perhaps the only way to mitigate this type of failure is to ensure that any anomaly protection is disabled that could inadvertently shutdown engines or other critical systems. Another mitigation technique is to ensure sufficient redundancy exists in critical components and computers needed for critical maneuvers. This latter failure scenario could occur in any transportation architecture and therefore adequate system and reliability margins always need to be built into the hardware.

C. Planetary Spaceport Locations

The Earth-Moon L–1 libration point, which has the Moon's period, but is closer to the Earth, has been considered in the past for the Earth Spaceport location. The advantage of L-1 is a lower orbital velocity than the Moon, and therefore a lower required plane change delta-V. The problem with L-1 for Earth-to-Mars transportation, however, is that it is tied to the Moon's geometry; having the same period of about 28 days. For this reason, it is almost always in the wrong position in its orbit for the first maneuver for a trans-Mars injection or a hyperbolic rendezvous sequence. For the L-1 location, the Earth Spaceport could be almost a month off from its required position. This position mismatch can be mitigated by either high delta-V, which negatively impacts mission performance, or very long phasing orbits, which require excessive crew time in the Taxi; neither option being desirable.

Instead, a *roaming* Earth Spaceport is proposed that is in a relatively high orbit, which can move itself into the optimum hyperbolic departure position at the correct departure time. This positioning is accomplished by changing the period of the Earth Spaceport to cause it to drift to the required longitude over a period of months, and then reverting back to its original period. This phasing velocity is proportional to drift time, about 1 m/s for 1 deg over a period of a month, and can easily be carried out with low-thrust IPS. We have chosen Moon orbit radius (MOR) as the Earth Spaceport location since lunar resources are being used in this architecture and the transport energy between the Moon and this location is very low.

At Mars, the Spaceport is located near Phobos to be near its resources of which certainly oxygen, and most likely water, is available. In fact, if water is available, Phobos is a far more desirable object than a near Earth asteroid for exploitation of resources for Mars transportation. Because the Phobos orbit period is only about 7.5 hr, its period is short enough to accommodate significant launch time variations for Taxis departing Mars. In other words, launch periods of hours to days are feasible leaving Mars.

D. Ion Propulsion Trajectories

Low-thrust, ion drive propulsion, utilizing mass-efficient solar powered xenon ion engines, is applied to the transportation architecture in four areas: (1) midcourse shaping maneuvers of the Escalator orbits on which the Astrotels fly; (2) Spaceport orbit phasing maneuvers, (3) round-trip Cargo Freighters to resupply the Astrotel vehicles in transit; and (4) round-trip Cargo Freighters to resupply the infrastructure at Mars. Figure 6 illustrates the use of low-thrust propulsion on two such orbits as seen from the north ecliptic pole. The left set of orbits in Figure 6 shows the region of the Astrotel orbit where low-thrust is applied in order to carry out the periodic shaping maneuvers. The right set of orbits of Figure 6 shows the trajectory of the Astrotel Cargo Freighter from its Earth spiral departure until it rendezvous with the Astrotel. The use of low-thrust delta-V is ideal for these orbits where high-thrust is not needed, flight time is not critical, and huge savings in propellant mass can be achieved.

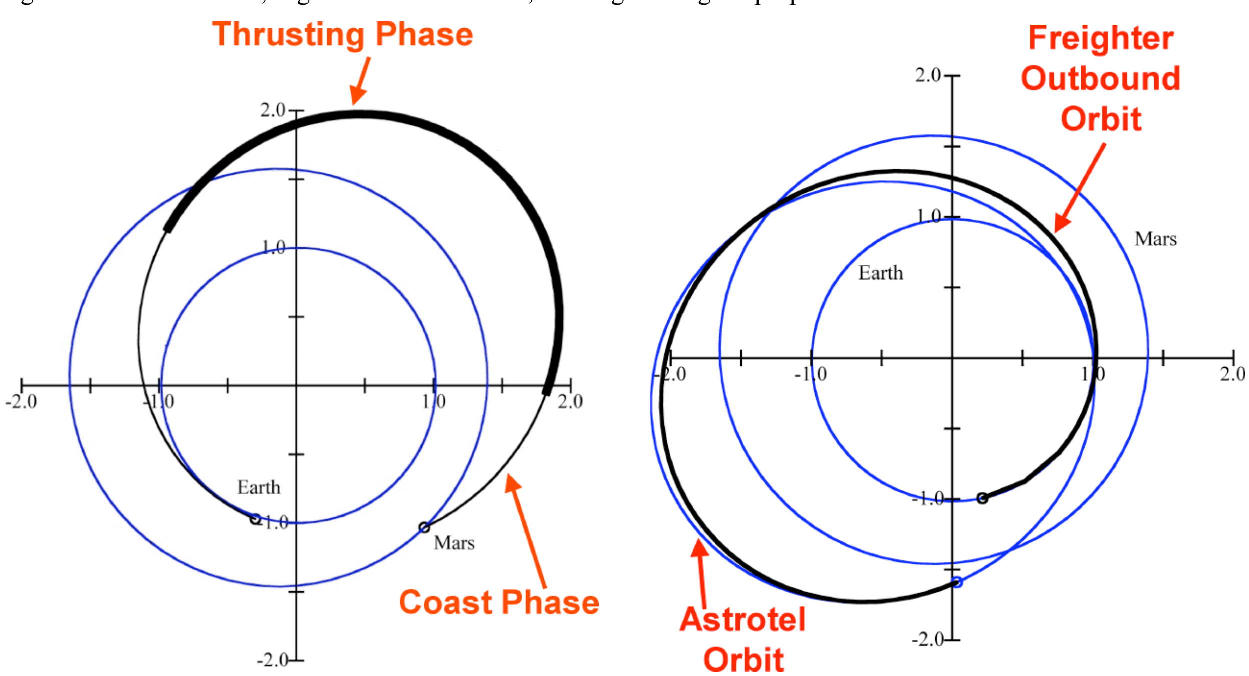


Figure 6 Low-Thrust Maneuvering on Orbits. The left set of orbits illustrates the Astrotel low-thrust orbit shaping and the right set of orbits illustrate the Astrotel Cargo Freighter low-thrust maneuvering and rendezvous

IV. Transportation Architecture Infrastructure

The interplanetary transportation architecture infrastructure includes Astrotels, Spaceports, Taxis, a Common Crew Module, Mars Shuttle, and interplanetary Cargo Freighters.

A. Astrotels

Astrotels are highly autonomous, only transport crew and other high value cargo, use highly efficient solar electric ion propulsion systems (IPS) for periodic orbit shaping maneuvers, and do not require artificial gravity since crew transit times are short. The Astrotel mass is about 70 mt, including IPS, radiation shielding, habitation, storage, power, and emergency escape pod, about one sixth the mass of the ISS. Keeping its mass low significantly reduces the total propulsive energy budget required for course corrections to only about 3-mt for all major corrections over 15 years. The 70-mt Astrotel mass includes a habitability module for a crew of ten. The size of this system provides a crew volume of more than 34 m^3, ~6-times the volume available to Space Shuttle crews, but only about 1/3rd of the crew volume of the ISS, assuming a 10-person crew. So the crew space is small, but the crews are going to and from Mars, not looping around the Earth forever. Figure 7 is a computer drawing of one concept for an Astrotel. The Hab Module is based on the Transhab Module concept (Ref. 6). The two smaller modules between the Hab Module and the solar array are pressurized cargo bays. The Cargo Freighter autonomously delivers all cargo to the Astrotel contained within a standard cargo bay. These are pressurized modules to facilitate crew unloading of consumables and RRU hardware. Once emptied, the cargo bay can be discarded or used to provide added crew volume like zero-gee squash courts. Table 2 summarizes the Astrotel components and their masses.

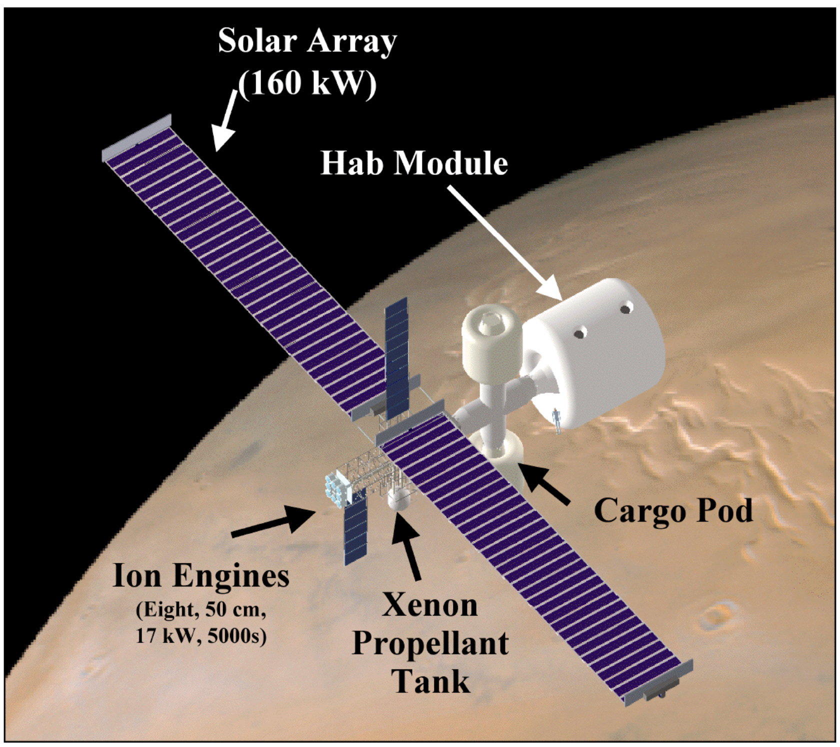


Figure 7 Astrotel Concept

B. Spaceports

Spaceports are collection points for the arrival and distribution of humans, cargo and propellants destined for transport to planet or natural satellite surfaces or to orbiting Astrotels. In this architecture, a Spaceport is based on the Astrotel design. Crew stay times are limited in order to minimize effects of zero-g. Crew maintenance is minimized by maximum application of autonomy in order to shorten crew stay times. Station-keeping, orbit corrections, orbit-phasing delta-Vs could easily be performed by the same or even smaller IPS system envisioned for the Astrotels. The size, configuration and mass of Spaceports are assumed approximately the same as the Astrotels. One major difference from Astrotels is that at or adjacent to each Spaceport are propellant storage and transfer facilities.

Table 2 Astrotel Equipment Mass Summary

Subsystem or Item	Dry Mass	Consumables	Subtotal Mass
Physical/Chemical Life Support	2,778	3,840	6,618
Crew Accomodation	5,000	4,224	9,224
Structure	5,500		5,500
EVA Equipment and Consumables	1,183	446	1,629
Communications and Information	320		320
Thermal Control	550		550
Power	785		785
Propulsion	644		644
Attitude Control	500		500
Radiation Shielding	9,254		9,254
Escape Pod and Reserve	22,000		22,000
Crew	1,200		1,200
Utility Module Base	5,000		
Permanent Cargo Bay	3,000		
Spares	2,100		2,100
Total Mass	**59,814**	**8,510**	**68,324**

C. Taxis

Taxis provide crew transportation between Spaceports and Astrotels. In order to minimize propulsive energy use, Taxis use aerocapture techniques for getting into planetary orbits. Aerocapture takes maximum advantage of planetary atmospheric drag to slow the vehicle on its approach from interplanetary space. The key sizing assumptions are: a.) minimal radiation protection for the crew is provided since transfer times to/from the Astrotels is less than 10 days, b.) no cargo is transported to the Astrotel by the Taxi, c.) 15% of the entry mass is aeroshell or heat shield, d.) LOX/LH propulsion system at a specific impulse of 460 s and thrust of 60,000 lbs./engine, e.) fuel cell energy storage, and f.) propellant tank augmentation (expendable drop tanks and, in some cases, additional engines) is required upon leaving Mars. Taxis escape planets on hyperbolic trajectories to rendezvous with Astrotels. Rendezvous time to Astrotels is measured in days in order to reduce the duration of crew time in the expected cramped quarters, since crew volume is comparable to Apollo, and since radiation shielding is minimal. Figure 8 illustrates a Taxi performing aerocapture at Mars with its three rocket engine nozzles retracted behind the aeroshell. Figure 9 illustrates the crew module that is common with the Taxi and the Mars Shuttle vehicles.

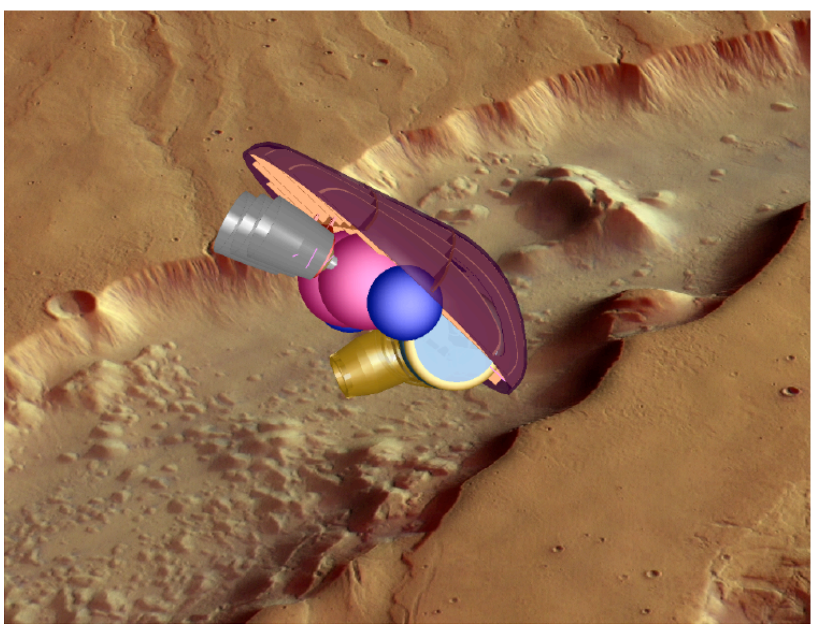


Figure 8 Taxi performing an aerocapture maneuver at Mars

The Taxi on departure from Mars is either a two stage vehicle (3 of 7 opportunities) or three stage vehicle (4 of 7 opportunities) of which the last stage is the basic vehicle similar to that shown in Figure 8..The Taxis are assumed to be propelled with three advanced Pratt & Whitney RL 60 engines, rated at 60,000 lbs. each. The engines are gimbaled ±5°, both vertically and horizontally. All three engines are shown installed in a common frame with individual gimbals and actuators for each engine.

To reduce development costs, this transportation architecture incorporates a Common Crew Module that is installed within each Taxi and the Mars Shuttle, to be discussed later. Table 3 summarizes the system mass of the Common Crew Module. Table 4 summarizes the overall mass breakdown of the Taxi system. The Taxi vehicle uses aerodynamic orbit capture (aerocapture) at both Earth and Mars. The atmospheric entry speed at Earth is modest and the energy to be lost is consistent with a relatively short-duration aerocapture flight. At Mars, however, the atmospheric entry speed is much larger than the desired exit speed, so the Taxi flies a nearly constant altitude, lift-down trajectory in the atmosphere, counteracting centrifugal force, until enough energy is depleted before turning lift up and exiting the atmosphere. A vehicle with relatively high lift-to-drag ratio is required at the start of the cruise in order to supply the required centripetal acceleration and to stay under a total g-load of about 5. The current baseline Taxi aeroshell is known as an elliptical raked cone (Ref 7) which has a maximum lift-to-drag ratio of 0.63. The crew is provided g-seats that rotate in order to accommodate the varying g-load direction and the different vehicle-relative thrust direction during propulsive maneuvers than for aerocapture maneuvers. The base vehicle is about 20 mt, dry. Fully loaded Taxis vary in mass from the single stage low delta-V Mars and Earth configurations of ~40 mt to the three stage high delta-V Mars configuration of ~300 mt; most of which is propellant.

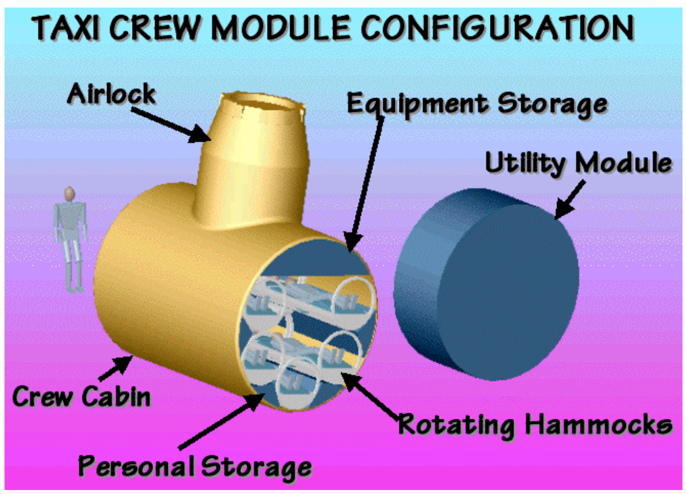


Figure 9 Common Crew Module cut-away

Table 3 Crew Module Mass Summary

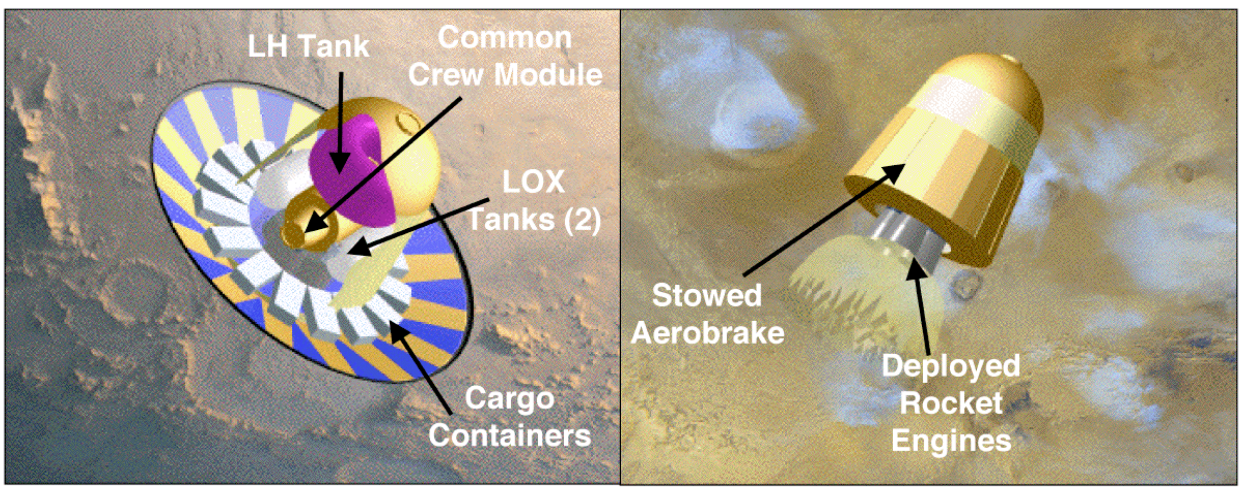
Crew Module System Element	Mass, kg
Crew Cabin	
Structure	1,431
Airlock plus Tunnel	810
Insulation, 30mm	188
Nav	100
Telem	100
Elect	100
Comm	50
Crew Accom	694
Crew Mass	818
Misc	200
	4,490
Utility Module	
ECLSS	121
Electrical Power	171
Subtotal	292
Total Mass	**4,783**

Table 4 Taxi System Mass Summary

Taxi System Element	Dry Mass, kg
Crew Module	7,207
Primary Structure	1,000
Propulsion	4,407
Subtotal	12,614
Aeroshell	2,967
Grand Total Dry Mass	**15,581**

D. Mars Shuttle

The Mars Shuttle transports a crew of 10 to and from the Mars Base and the Mars Spaceport near Phobos. The Mars Shuttle supports crew needs during the very short transit (<1 days) between the Mars Base and the Mars Spaceport. In addition, the Mars Shuttle carries out delta-V maneuvers, performs aero-entry and landing maneuvers within the Martian atmosphere, navigates autonomously during all maneuvers, provides electrical power to its subsystems and carries RRU cargo from the Mars Spaceport to the Mars Base. The Mars Shuttle is designed to travel only between the Mars surface and the Mars Spaceport at Phobos. The basic vehicle is a low lift/drag ratio design with a deployable 20-m diameter aerobrake used during entry and landing. At take-off, the aerobrake is stowed, or jettisoned on the surface, to reduce atmospheric cross-section and minimize drag. The low lift/drag ratio design offers reduced mass, ease of fabrication, reduced cost and growth accommodation over higher lift/drag designs. The Mars Shuttle mass is 67 mt fully loaded, 42 mt at entry, 32 mt landed and 22 mt dry. Figure 10 illustrates computer-generated designs of the Mars Shuttle in its entry and launch configurations.



(a) Mars shuttle at entry (b) Mars shuttle after launch

Figure 10 Mars Shuttle Configuration

E. Cargo Freighters

Interplanetary Cargo Freighters resupply the two Astrotels and the Mars Spaceport. Two types of cargo transporters are planned, an Astrotel Cargo Freighter and a Mars Cargo Freighter. These very similar vehicles deliver cargo from LEO to Astrotels and Spaceports. Cargo Freighters use xenon ion propulsion systems to spiral out of Earth orbit, shape their interplanetary trajectories to rendezvous with Astrotels or spiral into Mars orbit to Phobos. The Astrotel Cargo Freighter delivers a standard pressurized cargo bay module to the Astrotel. The cargo bay approach facilitates crew unloading.

The Cargo Freighter's solar arrays consist of multiple sets of identical Astrotel solar arrays (80 kW panels). The propulsion system shares a high degree of technology heritage with the Astrotel IPS. The following charts describe the design parameters for these important vehicle parameters.

Table 5 Astrotel Cargo Freighter Sizing

Mass of Cargo each trip to Astrotel	**17,225**	kg
Initial mass of Cargo Freighter in LEO	28,632	kg
Propellant Mass	7,928	kg
Final Mass of Freighter	3,479	kg
P_o	286.3	kW
Power/Propulsion Mass (M_{ps})	2291	kg

Table 6 Mars Cargo Freighter Sizing

Mass of Cargo each trip to Mars Spaceport	**38,106**	kg
Initial mass of Cargo Freighter in LEO	66,237	kg
Propellant Mass	19,851	kg
Final Mass of Freighter	8,280	kg
P_o	662.4	kW
Power/Propulsion Mass (M_{ps})	5,299	kg

V. Extraterrestrial Resources

The use of planetary resources significantly reduces the material that needs to be brought up through the gravity well of the Earth and delivered to a planetary transportation node. The energy required for transportation of propellant is proportional to the square of the velocity change that it must undergo. For example, the energy required conveying propellant from the Moon to L-1 is approximately 1/30th of that required from the Earth's surface to L-1 and requires a much simpler spacecraft. This transportation architecture includes the use of *in situ* resources at the Moon (lunar water ice), at Phobos (O_2 production, from carbon reduction of the regolith, or possibly water), and on the surface of Mars (heat extraction of water from regolith, electrolysis, O_2/H_2 liquefaction and storage). In addition, there are off-world processing and storage facilities including a water electrolysis, O_2/H_2 liquefaction and storage at the Earth Spaceport and O_2/H_2 storage at the Mars Spaceport. The baseline architecture requires resource production rates of 15.4 kg/hr of Phobos LOX, 6.6 kg/hr of Martian water, 10.2 kg/hr of lunar water, and 1.6 kg/hr of LOX/LH from lunar water at the Earth Spaceport. Production rates account for the lower duty cycle of planetary solar power (Phobos, Moon, and Mars).

It is a challenge to design excavation and extraction systems for Phobos, Mars and the Moon since they lack significant, or any, atmospheres, gravity is low to extremely low, and temperature variations are extremely high. In addition to operating under these extreme environments, a Phobos excavation system requires obstacle avoidance, rock sorting, continuous excavation duty cycle, excavator flexibility, and a low mass. A bucket-wheel excavator system (BWE) specifically designed for extraterrestrial environments, as shown in Figure 11, meets all these requirements (Ref. 8). The BWE excavates continuously and simultaneously transports the materials to storage. Excavation forces are primarily horizontal and provided by the mass of the entire excavator instead of only the bucket mass allowing the BWE to work in extremely low gravity without exterior anchoring, provided its mass provides ample traction for excavation and forward movement.

On the Moon and Mars relatively low temperatures (100°C to 500°C) are required to boil off the water from the soil (assumed in a 1% abundance by weight) after which is collected, liquefied and stored in preparation either for transport to the Earth Spaceport or for further processing into rocket fuel at Mars. At Phobos the soil is placed in a Carbothermal reactor where combined with high temperatures (1700 °C) and hydrogen and carbon, oxygen is produced. After producing the oxygen it is liquefied for eventual transport to the Mars Spaceport for long-term storage. If water is found on Phobos, which is likely, the resource infrastructure, and thermal requirements, could be much simpler and similar to the Moon.

Except for rocket fuels needed to launch from the surface of the Moon, producing LOX/LH from lunar water is done at the Earth Spaceport (by means of electrolysis and liquefaction) where an abundant supply of solar energy is available. Processing of Martian water occurs near the Mars Base after which LOX/LH are stored for use by the Mars Shuttle.

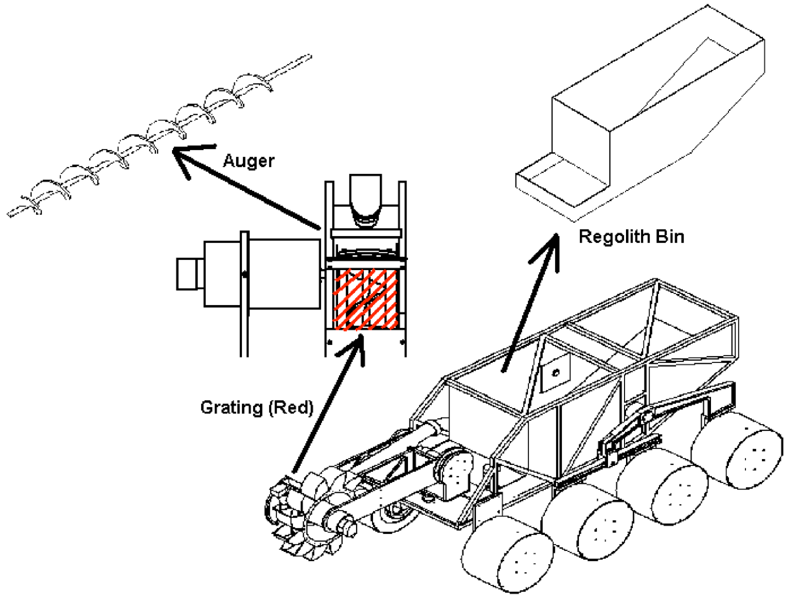


Figure 11 Bucket Wheel Excavator and Transporter

VI. Concept of Sustained Mars Transportation Operations

Figure 12 is a different view of the Escalator orbits relative to Earth and Mars. Figure 12 illustrates the location of the Up and Down Escalator Orbit Astrotels in relation to Earth and Mars as a function of time. The time axis, just for illustration, is from 2012 through 2027, and the sequence repeats every 15 years. In this view, the vertical axis is offset planet distance from the sun so we can better see each of the two orbits. Earth is shown as a dashed green line at a 1 AU and 3 AU (plus a 2 AU vertical offset) solar distance and Mars is shown as a dashed red line at an average solar distance of 1.52 AU and 3.52 AU (plus a 2 AU vertical offset). The top set of wiggles corresponds to the position of the Up Escalator Orbit (UEO) Astrotel as a function of time and solar distance plus a 2 AU vertical offset. The bottom curve records the location of the Down Escalator Orbit (DEO) Astrotel without any vertical offset. The black numbers refer to crews going to and from Mars. For example, the second crew (#2) departs Earth and rendezvous with the UEO Astrotel in late December 2013 and arrives at Mars around mid May 2014. Crew #2 departs Mars on the DEO Astrotel in early July 2018 and arrives back at Earth early December 2018. Tour of duty is about 5 years with about 4 years and two months spent in the vicinity of Mars. Crews overlap so that there is usually always 20 crew occupying the Mars Base at a time, except for about 1 month near crew transfer times.

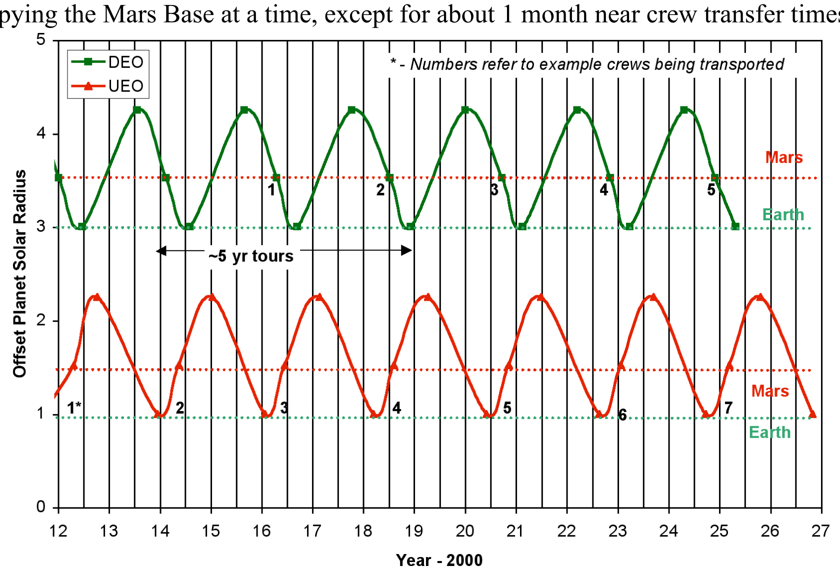


Figure 12. Escalator orbital sequence relative to Earth and Mars.

Figure 13 illustrates about 5 years of operations of the UEO and DEO along with their associated Astrotels, Spaceports, Taxis and Shuttles. The Earth is represented by the bottom of the chart with Mars at the top. The relative locations of the Spaceports and LEO Space Station are shown. The yellow circles represent transfer points. A crew initially launches in a Shuttle to a Space Station in LEO in late 2027 where they transfer to an exoatmospheric Taxi that takes them to the Earth Spaceport in orbit around the Earth at lunar distance. At the appropriate time, the crew departs the Spaceport toward a hyperbolic rendezvous with the UEO Astrotel. Five months later, the crew leaves the Astrotel via a Taxi and targets it for an aerocapture maneuver within the atmosphere of Mars. The taxi exits the Martian atmosphere with just the right amount of energy to reach Phobos orbit, where the Mars Spaceport is located. At the Mars Spaceport the crew, along with cargo brought by Cargo Freighters, transfers to a Mars Shuttle for a direct entry trip to the Mars Base.

The next crew to return to Earth around March of 2029 departs Mars in the Mars Shuttle and arrives at the Mars Spaceport a few hours later. The crew transfers to a Taxi that departs Mars and rendezvous with the DEO Astrotel a few days after departing the Spaceport. After a 5 month trip, the crews reenter the Taxi and depart the Astrotel on a aerocapture trajectory at Earth. The aerocapture maneuver at Earth could target the Taxi to a rendezvous with the Earth Spaceport at lunar distance or the LEO Space Station where crews transfer to the Earth Shuttle for at short trip to the surface of the Earth.

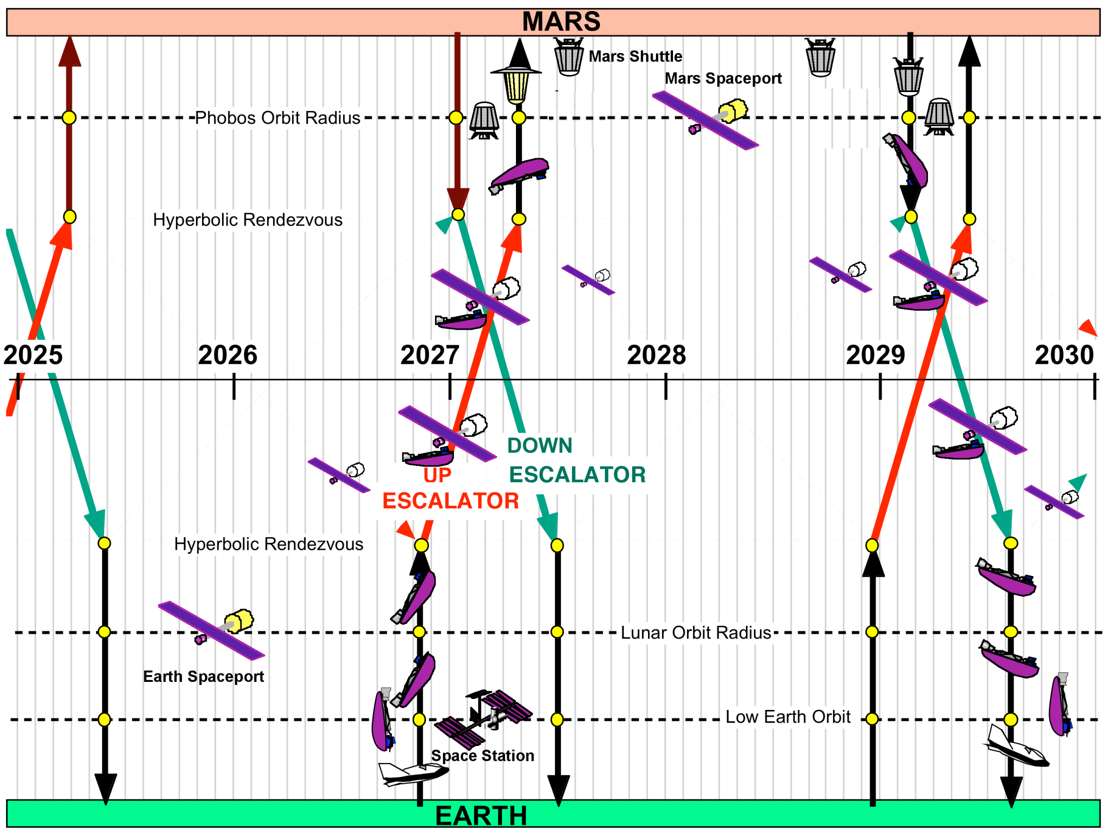


Figure 13. Mars transportation CONOPS.

VII. Life-Cycle Costs

A computerized model has been developed that describes the baseline architecture and a number of options and generates life-cycle cost (LCC) estimates (Ref. 1). The model is highly integrated and interrelated including transportation vehicles; ground systems; subsystem technology assumptions; *in situ* resource assumptions and systems; and celestial mechanics analysis. The model was developed to facilitate integration of various system elements, to facilitate overall architecture trade studies and to support life cycle cost analysis.

This approach allowed independent development of individual elements and supporting analyses by focusing on the relationships among the system elements and establishing element-to-element links for selected inputs/outputs. A detailed work breakdown structure was developed including Advanced Technology Development, Flight System

Development, Launch and Operations. Costs were tracked at one and two levels below the main categories. Cost references were a mix of actual data from past missions and component-level performance parametrics developed by technology specialists in NASA, industry and academia. The 30-year operations costs for the transportation architecture options were used. This model performs trade studies so one can vary system capabilities or architecture assumptions and hence compare cargo mass and *in situ* resource requirements and eventually life-cycle costs. In the current version of the model, there are over 100 individual sub elements.

This model is best at comparing life-cycle costs of different architecture options. Several cost estimates were generated, varying a number of assumptions including (a) launch costs ($2k or $10k) and (b) with and without ISRU. These cost estimates are compared in Figure 14 below assuming FY12 dollars. Note that for launch costs of $2k/kg there is not a significant benefit of ISRU in lowering LCC. However, when launch costs are $10k/kg the difference is greater between the ISRU and non-ISRU cases.

The baseline transportation scenario ($10k/kg and ISRU) life-cycle cost of $197.8 B is split between $5.8 B for advanced technical development, $101.5 B for flight system development, $8.2 B for initial launch services and $82.3 B for launch and operations over 30 years. The total sustained operations costs are estimated at $2.75 B per year, or about 15% of the 2012 NASA budget. Based on operations costs and the average number of people visiting Mars in 15 years, the cost per crew member to Mars is about $0.55B.

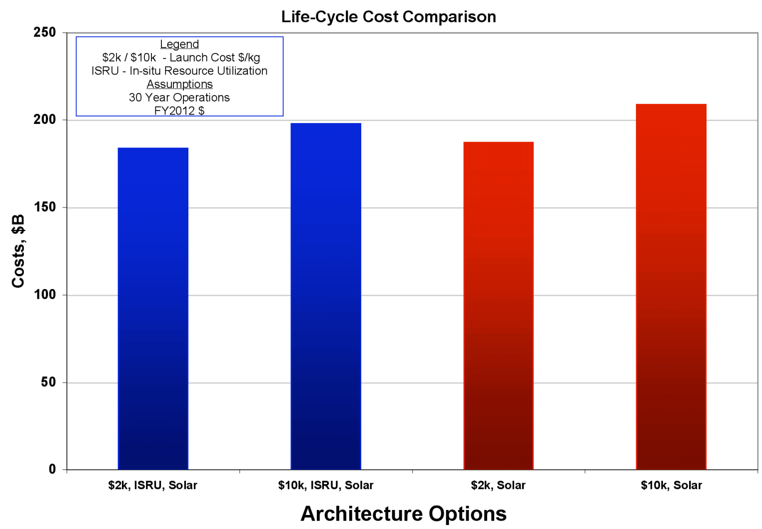


Figure 14 Life-Cycle Cost Comparison with Architecture Options

VIII. Conclusion

This interplanetary express transportation architecture concept provides a framework and context for future technology advance and robotic mission exploration. If one can envision an optimized interplanetary transportation systems architecture, then one can take steps today that will enable it. These steps could include establishing key technology goals to insure technology advance meets the future need. Other steps include embarking on robotic pathfinder missions to explore Mars, Phobos and the Moon and to search for *in-situ* resources, and their state, that are useful in any transportation systems architecture. For example, water exists on the Moon, possibly within Phobos and at Mars. However, the exact state of the water concentration, whether bound or not, is unknown. The existence of extraterrestrial water on these bodies will have a dramatic impact on future plans and technology development for near-Earth exploitation and Mars exploration. Water broken down into its component molecular states of oxygen and hydrogen is rocket propellant. The existence of readily available and accessible extraterrestrial resources will have a profound impact on our initial steps into the Universe by making Man less dependent on Earth.

Finally, this concept enables frequent, express trips to Mars by scientists and explorers. Opportunities for extended direct and teleoperated field science (e.g. geology) by scientists at Mars will swiftly expand scientific knowledge of the planet and increase our understanding of its similarities and differences with our own planet. This transportation architecture offers transport to and from Mars at an expected low life cycle cost that will not limit Mars exploration, like the success of Apollo ended lunar exploration. With low life cycle costs, permanent exploration and inhabitation of Mars will be cost effective. Furthermore, this express transportation architecture contributes to the establishment of a permanent human presence on the planet Mars, our most hospitable neighbor.

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