Paper Number: 03 ICES-2392

Interplanetary Rapid Transit to Mars

Kerry Nock, Angus McRonald, Paul Penzo, and Chris Wyszkowski
Global Aerospace Corporation

Michael Duke, Robert King, Lee Johnson
Colorado School of Mines

Mark Jacobs, Jerry Rauwolf
Science Applications International Corporation

ABSTRACT

A revolutionary interplanetary rapid transit concept for transporting scientists and explorers between Earth and Mars is presented by Global Aerospace Corporation under funding from the NASA Institute for Advanced Concepts (NIAC) with support from the Colorado School of Mines, and Science Applications International Corporation. We describe an architecture that uses highly autonomous spaceships, 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 low-thrust cargo freighters. In addition we discuss the production of rocket fuels using extraterrestrial materials; aerocapture to slow Taxis at the planets; and finally describe a number of trade studies and their life-cycle cost results.

INTRODUCTION

Someday scientists and explorers will regularly travel to Mars for research and exploration as they now travel to Antarctica. Knowing this eventuality enables us to plan for the future. As with the South Pole Base at Antarctica, an efficient transportation system will be needed to rotate crews back and forth between Earth and Mars and to resupply equipment and fuels.

Global Aerospace Corporation and its partners have developed an innovative architecture that uses highly autonomous, solar-powered, xenon ion-propelled spaceships, dubbed Astrotels; small Taxis spaceships for trips between Astrotels and planetary Spaceports; Shuttles that transport crews to and from orbital space stations and planetary surfaces; and low-thrust cargo freighters that deliver hardware, fuels and consumables to Astrotels and Spaceports. Astrotels can orbit the Sun in cyclic orbits between Earth and Mars and Taxis fly hyperbolic planetary trajectories between Astrotel and Spaceport rendezvous. Together these vehicles transport replacement crews of 10 people on frequent, short trips between Earth and Mars. Two crews work on Mars with alternating periods of duty, each spending about 4 years there with crew transfers occurring about every two years. The production of rocket fuels has been studied using materials mined from the surfaces of the Moon, Mars and the Martian satellites. The use of the atmospheres of the planets themselves to slow Taxis, called aerocapture, has been developed and analyzed. A tool has been constructed that can estimate the life-cycle cost of a transportation architecture and its various options.

This concept provides a framework and context for future technology advance and robotic mission exploration. The human exploration program could benefit from a focus on permanent Mars habitation, instead of brief and expensive expeditions; lunar and Phobos exploration as steps to Mars; and evolutionary vehicle and system development toward a Mars transportation infrastructure. The inevitability of human Mars exploration will be much closer once we begin taking these steps.

MARS BASE TRANSIT STOP

The level of capability envisioned at the Mars Base supports significant surface activities in the areas of science exploration, resource surveys, life-cycle maintenance, propellant production, and materials processing and fabrication. These activities will take place at one or two fixed-site facilities on Mars and on distant traverses from the base. Such operations will 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 crew complement of 20 on the Martian surface will carry out these activities; the resident population at any time could fluctuate substantially from the average depending on the phase of the crew rotation cycle dictated by the interplanetary transportation orbit options. The Mars surface is assumed to be continually inhabited thereby requiring staggered crew rotations and, thus, overlap between "experienced" and "fresh" personnel. Figure 1 illustrates one base concept and illustrates an example equipment list (where mt is metric tonne or 1000 kg).

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 will be extracted from the soil and atmosphere as needed. Agriculture, in greenhouses, and aquaculture will supply 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 the Mars Spaceport are created in situ. The entire Mars Base requires delivery of about 280 metric tonnes (mt) of hardware to the surface in the build up phase 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 this Mars transportation system architecture.

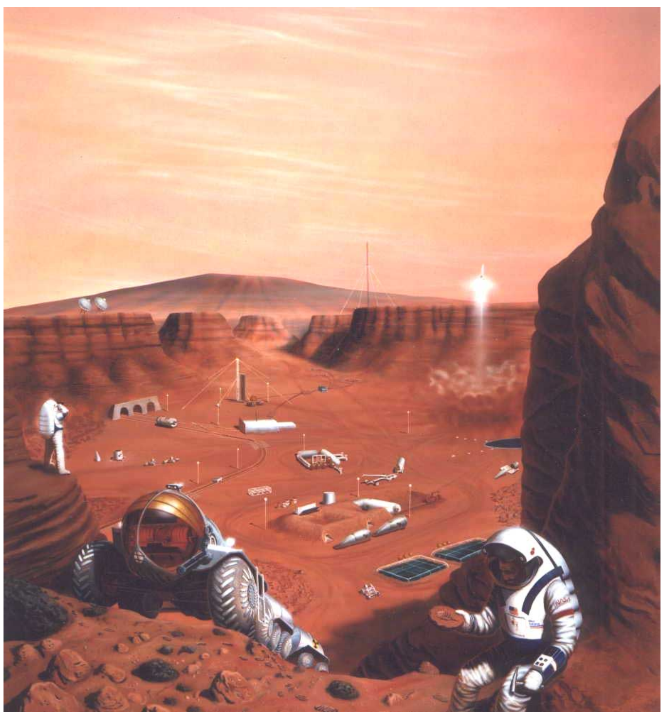


Figure 1 Artist Concept of a Mars Base

Table 1 Mars Base Systems Mass Summary

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
Subtotal			**155.8**
Mission Support Systems			
120 kW Solar Array - @100W/kg	2	1.2	2.4
Power Management, & Distribution	2	0.3	0.6
Energy Storage (NRFC packages)	2	1.0	2.1
Suitup/Maintenance Facility	2	1.8	3.6
Pressurized Transporter	3	9.1	27.3
Open Rovers	3	1.0	3.0
Inflatable Shelter w/Airlock	10	0.5	5.0
Communication Satellites	3	0.8	2.4
Crane	2	5.0	10.0
Trailer	2	2.0	4.0
Subtotal			**60.4**
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
Robotic Rovers	10	0.2	2.0
Weather Station	5	0.2	1.0
Survey Orbiters	2	0.8	1.6
Subtotal			**62.6**
Total			**278.8**

SPACE TRACKS

Cycling orbits can be designed to enable sustained human interplanetary transportation through regular encounters with Earth and the target planet or between Earth and the Moon. Several interplanetary cycler orbit concepts have been developed over the last two decades to support studies of sustained Mars operations. Cyclers (Aldrin, 1985; Hoffman, 1986; and Nock, 1987) and the classic Stopover trajectories (Penzo, 2002b) are two types of orbits that have received high interest for use in Mars transportation scenarios. The Aldrin cycler orbit type can be seen as viewed from the North Ecliptic Pole in Figure 2.

The Aldrin Cycler orbits have a period that is approximately equal to the Earth-Mars synodic period (26 months) and, when the line of apsides is rotated by gravity assist methods (average of about 51.4° each orbit), will enable Earth-to-Mars and Mars-to-Earth transfers every 26 months. Aldrin Cycler orbits come in two types, an Up Cycler and a Down Cycler orbit. The Up Cycler has the fast transfer occurring on the Earth to Mars leg while the Down Cycler is just the reverse. Fig.2 illustrates both orbit transfer geometries. When two Astrotels are used, an Aldrin Cycler provides relatively short transit times (~5 months) and regular transit opportunities. However, the planetary encounters occur at high relative velocities and typically, impose harsher requirements on the Taxi craft than other cyclers. Also, the Aldrin Cycler requires a modest mid-course correction on 3 out of 7 orbits to maintain the proper orbit orientation. These delta-Vs will be carried out using low-thrust, solar powered ion propulsion systems (IPS).

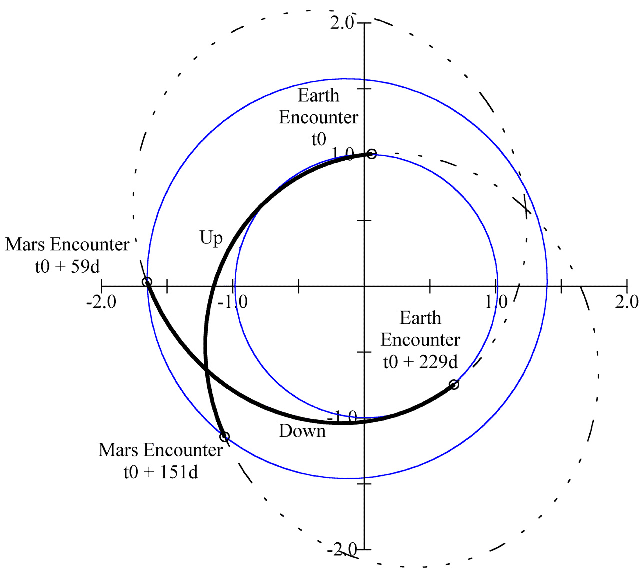


Figure 2 Aldrin Cycler Orbits

Stopover Cyclers are direct transfers from Earth to Mars with high-thrust propulsive maneuvers at both ends of the trajectory and a stop at each planet. Stopover Cyclers require two Astrotels operating. Flight time varies between 4-7 months depending on opportunity and propellant loading. Stay time at Mars is identical to the Semi-cyclers or about 1.5 years. Advantages of Stopover Cyclers are low departure and arrival velocities for a given flight time, flexible launch and arrival dates, elimination of the hyperbolic rendezvous, close vicinity of the station to the planet for replenishment and refurbishment, and alternate mission uses for the stations while in orbit about each planet, waiting for the next opportunity to return.

At this time, the Aldrin Cycler orbits have been selected as the reference because of several key advantages. One advantage is that Astrotels do not require high-thrust chemical propulsion systems, whereas, in the Stopover Cycler concept, high-thrust propulsion must be used to keep the flight time short. Another important advantage of Aldrin Cyclers is that the Astrotels never stop. The implication of this advantage, combined with the use of low-thrust systems, is that one can incrementally increase the Astrotel capability 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 the low-thrust Aldrin Cyclers, only two Astrotel vehicles need to be constructed and maintained.

GETTING ON AND OFF THE TRAIN

Cycler orbits with Earth and Mars hyperbolic flybys necessitate transfers between a planetary Spaceport and an Astrotel via a Taxi vehicle. The Astrotel flyby is completely constrained in periapsis date, distance, and inclination, since it must continue to travel on its desired cycler path between the planets. One of the major concerns in the use of cyclers for human transportation has been the hyperbolic rendezvous where the Taxi departs the Earth with a near instantaneous launch period without any margin for error or hardware delay. The primary restriction here is that the rendezvous must take place within about 7 days from the time of departure from the Spaceport because Taxi vehicles have limited consumables and life support and are lightly shielded against radiation. Figure 3 (adapted from Penzo and Nock 2002a) shows the Spaceport orbit, the Astrotel flyby and three Taxi hyperbolic rendezvous options. We have selected the 3-burn option for the reference because it requires a low total delta-V and a short flight time. The 4-burn option has a lower delta-V however a prohibitively long transit time for a Taxi. The 3-burn option consists of a Taxi departure maneuver, ΔV_1, to lower periapsis altitude for the injection delta-V, ΔV_2, followed several days later by the rendezvous maneuver, ΔV_3.

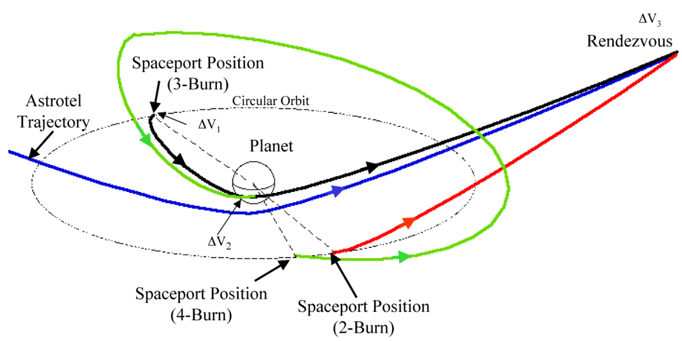


Figure 3 Hyperbolic Rendezvous Options

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 almost 8 km/s, whereas at lunar distance, the velocity is about 1 km/s, which is a better place to make a required plane change.

TRANSIT STATION LOCATIONS

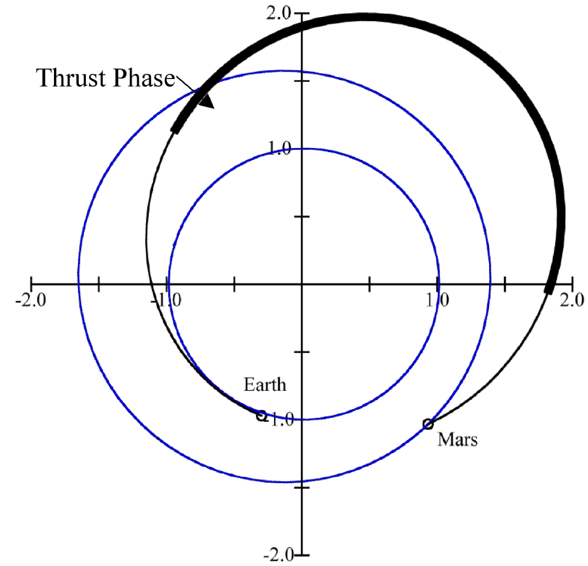
The Earth-Moon L–1 libration point, which has the Moon's period, but is closer to the Earth, has been considered in the past for the Earth Spaceport location. The advantage of L-1 is a lower orbital velocity than the Moon, and therefore a lower required plane change delta-V. The problem with L-1 for 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 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.

An ***active*** Earth Spaceport is needed 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 Lunar orbit radius (LOR) as the Earth Spaceport location for the current studies since we are using lunar resources, though other high Earth orbits are also candidate Spaceport locations.

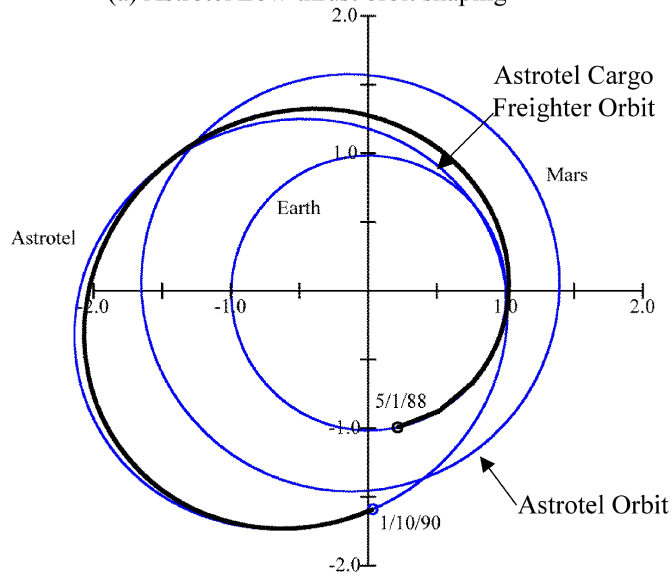
The Mars Spaceport is located near Phobos (to be near its resources). Because the Phobos orbit period is only about 7.5 hr, it's period is short enough to accommodate significant launch time variations for Taxis departing Mars. In other words, launch periods of hours to days are feasible leaving Mars.

ION DRIVE ENGINES

Low-thrust, ion drive propulsion, utilizing mass-efficient solar powered ion engines, is applied to the Astrotel architecture in four areas: (1) midcourse shaping maneuvers of the Astrotel orbits; (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 4 illustrates the use of low-thrust propulsion on such two orbits (with representative dates). Figure 4a shows the region of the Astrotel orbit where low-thrust is applied in order to carry out the periodic shaping maneuvers. Figure 4b 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 considerable savings in propellant mass can be achieved.



(a) Astrotel Low-thrust orbit shaping



(b) Astrotel Cargo Freighter low-thrust maneuvering and rendezvous

Figure 4 Low-Thrust Maneuvering on Orbits

HOTEL, TRANSIT STATION, TAXI, SHUTTLE AND FREIGHTER DESIGNS

This section describes various elements of the interplanetary transit system beginning with Astrotels.

ASTRONAUT HO**TEL** OR ASTROTEL

Astrotels are highly autonomous and transport only human and other high value cargo, use highly efficient solar electric propulsion for periodic orbit shaping maneuvers, and do not require artificial gravity. These features keep the size of these vehicles down to about 70 mt including IPS, radiation shielding, habitation, storage, power, and emergency escape pod. Reducing its mass significantly reduces the total propulsive energy budget required for course corrections to the 2767-kg propellant required for all major corrections over 15 years. The 70-mt mass includes a habitability module for a crew of ten. The size and volume of this system would provide a crew volume of about 6-times that available to today's Space Shuttle crew. Figure 5 is a schematic of one concept for an Astrotel that is approaching Mars. The two smaller modules between the TransHab and the solar array are cargo bays. The Astrotel 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 could be discarded or used to provide added crew volume. Table 2 summarizes the Astrotel components and their masses.

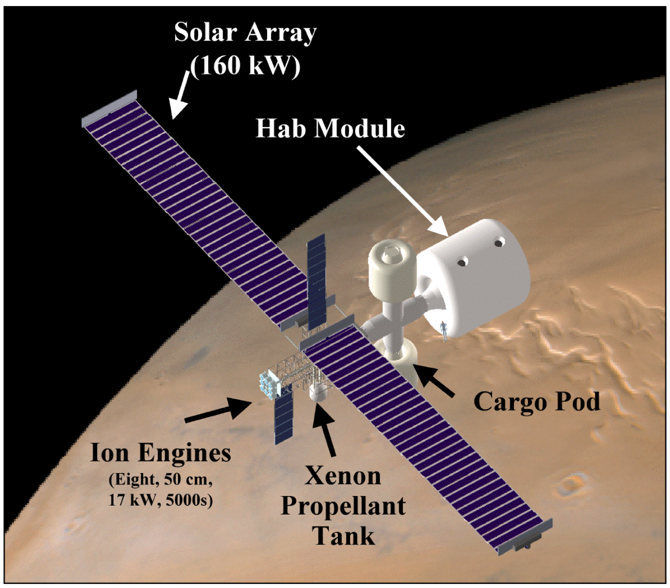


Figure 5 Astrotel Concept

TRANSIT STATIONS

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 cycling Astrotels. In past architectures such Spaceports were large, rotating, permanently crewed platforms. In this new concept, a Spaceport is based on the Astrotel design philosophy. 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 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.

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**

TAXIS AND USING THE ATMOSPHERE TO PUT THE BRAKES ON

Taxis provide transportation between Spaceports and Astrotels. In order to minimize propulsive energy use, Taxis use advanced aeroassist technologies for planetary orbit capture. Aerocapture takes maximum advantage of planetary atmospheric drag to slow the vehicle on its approach from planetary 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 7 days, b.) No cargo is transported to the Astrotel by the Taxi, c.) 15% of the entry mass is aeroshell, d.) LOX/LH propulsion system at I_{sp} of 460 s and thrust of 60,000 lbs./engine, e.) Fuel cell energy storage, no solar array power source, and f.) Propellant tank augmentation (expendable drop tanks and in some cases additional engines) is required at Mars. Taxis escape planets and are placed onto hyperbolic rendezvous trajectories 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. Figure 6 illustrates the Taxi departing Earth. Figure 7 illustrates the common crew module.

Table 3 summarizes the system mass of the common crew module. This crew module is used in both the Taxi and the Mars Shuttle, to be discussed later. 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 entry speed at Earth is modest and the velocity to be lost is consistent with a relatively short-duration aerocapture flight. At Mars, the entry speed is much larger than the exit speed desired, so that the aerocapture vehicle has to cruise around the planet at nearly constant altitude for a relatively long period. 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 vehicle is known as an elliptical raked cone (Scott, 1985) 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 quite different 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.

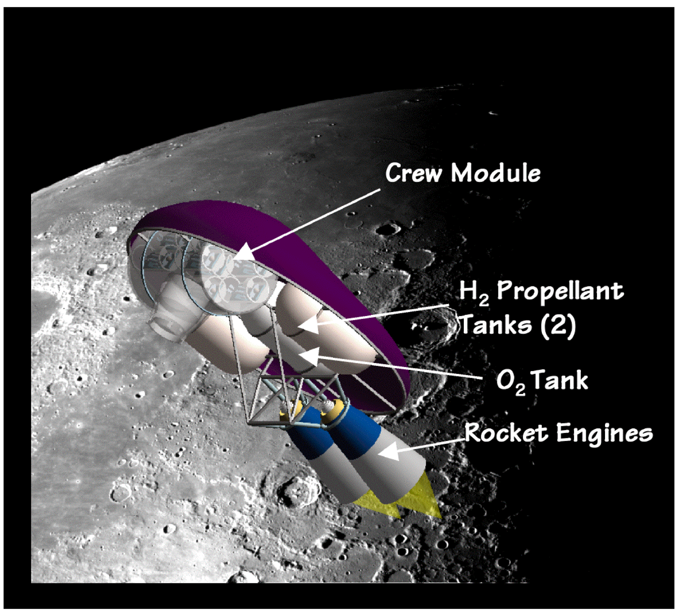


Figure 6 Taxi Leaving Earth

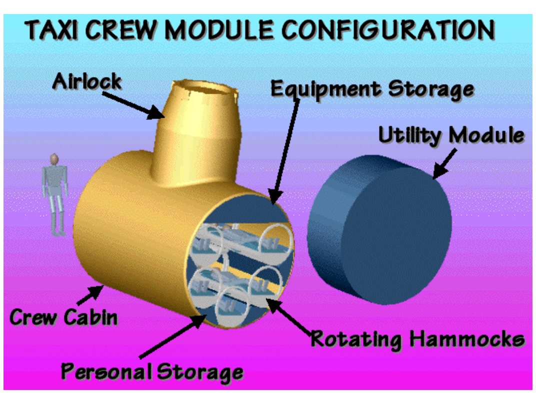


Figure 7 Common Crew Module Cut-away

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**

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 6. Figure 8 shows the 1st and 2nd stages of the three stage Mars Taxi with their augmentation tankage.

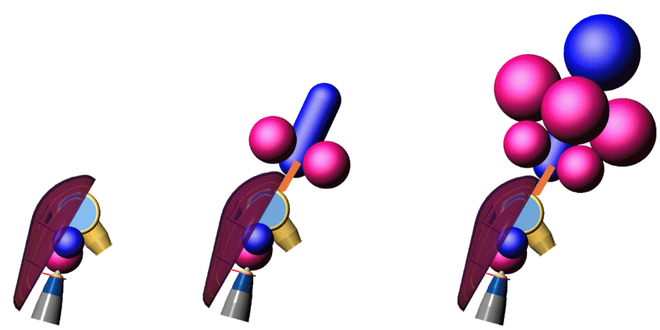


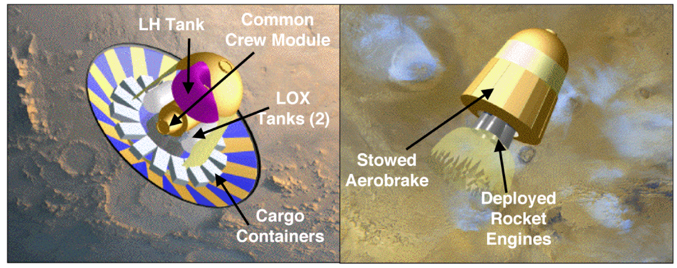
Figure 8 1st, 2nd, and 3rd Stage of Three Stage Taxi Departing Mars

The propellant tank configuration (blue = LOX and red = LH) was selected after evaluation of several solutions with the lowest mass of tankage and structure, compactness and simplicity of design in mind. The thrust vector of the engines passes through the vehicle's center of gravity requiring minimum engine gimbaling (within ±5 deg) during operation of all three stages, including 3^{rd} stage with empty tanks. All propellant tanks except the 2^{nd} stage LOX tank are spherical. The 2^{nd} stage LOX tank is cylindrical with hemispherical heads and performs dual functions: besides storing LOX it is used as the main structural element supporting all 1^{st} stage tanks and 2^{nd} stage LH tanks and transferring resulting forces to the 3^{rd} stage. Aluminum tank jackets includes multi-layer insulation (MLI). The 3^{rd} stage tanks (two LOX and two LH tanks) are supported by Aeroshell structure (reinforcing ribs). The shells are reinforced to properly distribute dynamic pressure and concentrated support loads. The 2^{nd} stage LOX tank is connected to two central Aeroshell reinforcing ribs similar to a boat keel. The attachments, besides small bending moment, are loaded with dynamic force resulting from the acceleration of the 1^{st} and 2^{nd} stages, transferred through 2^{nd} stage LOX tank shell and reinforcing rings. Four 2^{nd} stage LH tanks are attached to front reinforcing ring of the 2^{nd} stage LOX tank by tension members and supported on its rear reinforcing ring. Tension members are tangential to the respective tank shells. The 1^{st} stage LH tanks are similarly attached to the 1^{st} stage LOX tank and supported on the 2^{nd} stage LOX tank front reinforcing ring. The 1^{st} stage LOX tank, by far the heaviest component of the system, is supported from the 2^{nd} stage LOX tank front reinforcing ring. All the tanks are internally and/or externally reinforced so the concentrated as well as dynamic pressure loads are properly distributed to the shell.

The Taxi is propelled with three Pratt & Whitney RL 60 engines, rated at 60,000 lbs. each. The engines may be gimbaled ±5°, both vertically and horizontally. All three engines are shown installed in a common frame but in the future individual gimbals and actuators for each engine will be designed (an earlier two engine version of the Taxi is shown in Figure 6).

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 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 9 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 9 Mars Shuttle Configuration

TURNING PLANET DIRT INTO ROCKET FUEL

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 $1/30^{th}$ of that required from the Earth's surface to L-1 and requires a much simpler spacecraft. The transportation architecture includes the use of *in situ* resources at the Moon (lunar polar water ice), at Phobos (O_2 production from carbon reduction of the regolith), 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).

Excavation

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 the left of Figure 10, was found to meet all these requirements (Johnson, 2002). 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.

Extractors and Reactors

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.

Processing

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.

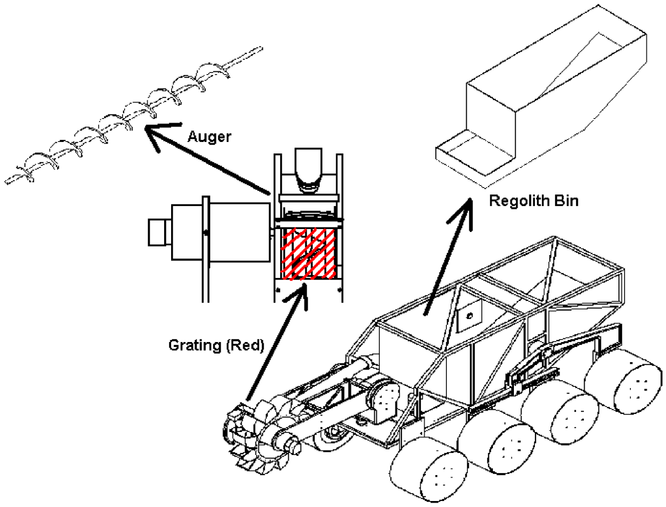


Figure 10 Bucket Wheel Excavator and Transporter

WHAT'S THE BEST TRANSIT SYSTEM AND HOW MUCH WILL IT COST TO OPERATE?

A computerized model has been developed that describes the baseline architecture and a number of options and generates life-cycle cost (LCC) estimates. These life-cycle estimates are best used to compare competing options rather than establishing credible estimates of the real total cost of such an architecture. 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 15-year operations costs for the transportation architecture options are displayed. This model can perform 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) basic trajectory type (Aldrin Low-thrust Cycler vs. Stopover Cycler), (b) launch costs ($2k or $10k), (c) with and without ISRU, and (d) use of solar or nuclear for surface and space power sources. These cost estimates are compared in Figure 11 below. It is interesting to note that the LCC for the solar option are substantially lower than for the nuclear option. The reasons for this are that the solar array power requirements, masses and costs are low and the nuclear systems are very expensive to develop even if small. If the power requirements had been substantially higher the nuclear option would look better. Another interesting thing to note is that for launch costs of $2k/kg there is not a significant benefit of ISRU in lowering LCC (one still needs to look at the operations costs to see if sustained operations costs would be significantly lower). However, when launch costs are $10k/kg there difference is much greater between the ISRU and non-ISRU cases. Figure 12 compares cost elements between the Aldrin and Stopover architectures. Of interest is the fact that the development costs are about $10 B less for the Stopover architecture, however the operations costs are higher.

The baseline Mars Astrotel scenario (Aldrin, $2k, solar, plus ISRU) life-cycle cost of $117 B is split between $5 B for advanced technical development, $69 B for flight system development, $1 B for launch services and $42 B for operations over 15 years. The total sustained operations costs are estimated at $2.8 B per year, or about 20% of the current NASA budget.

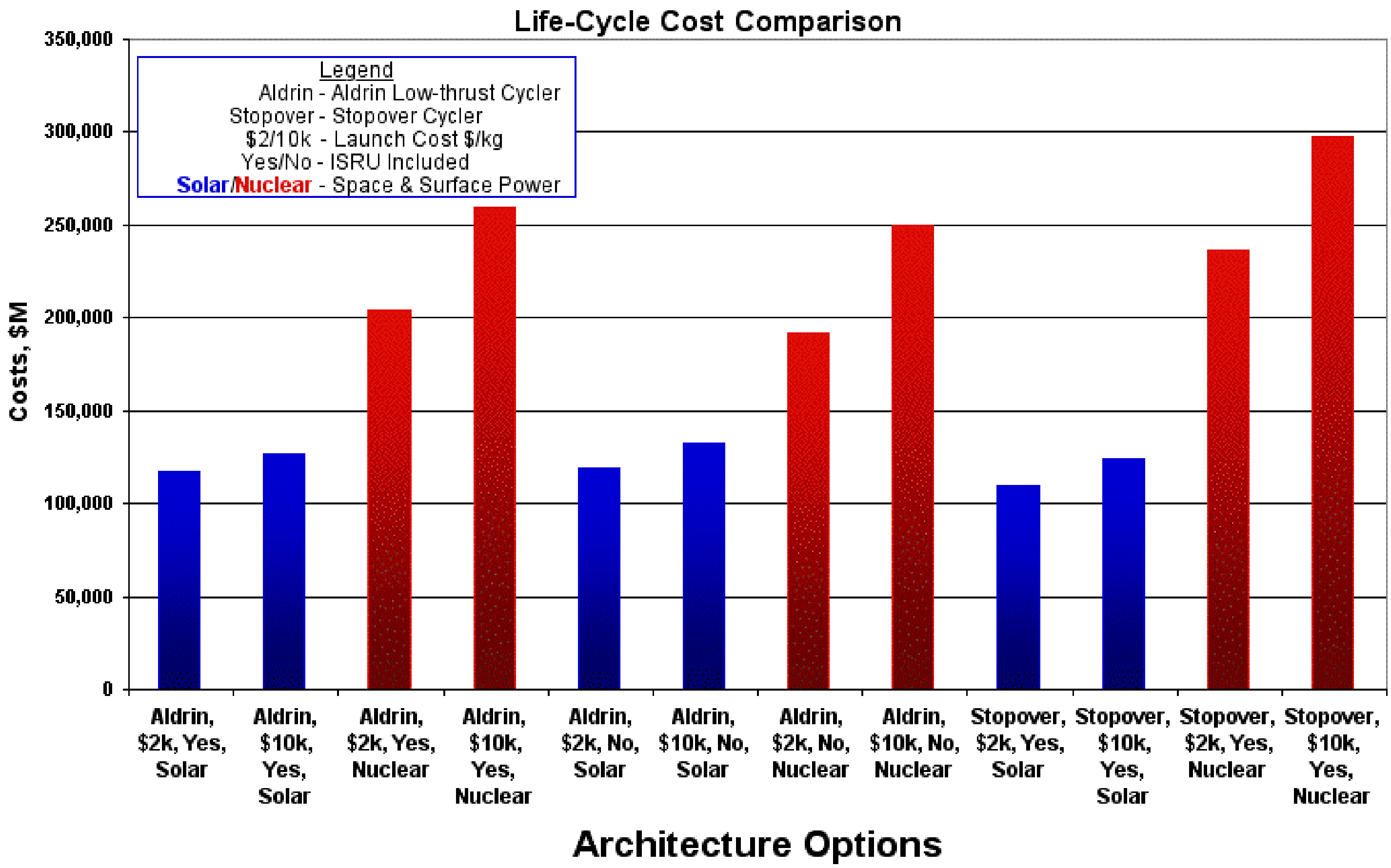


Figure 11 Life-Cycle Cost Comparison with Architecture Options

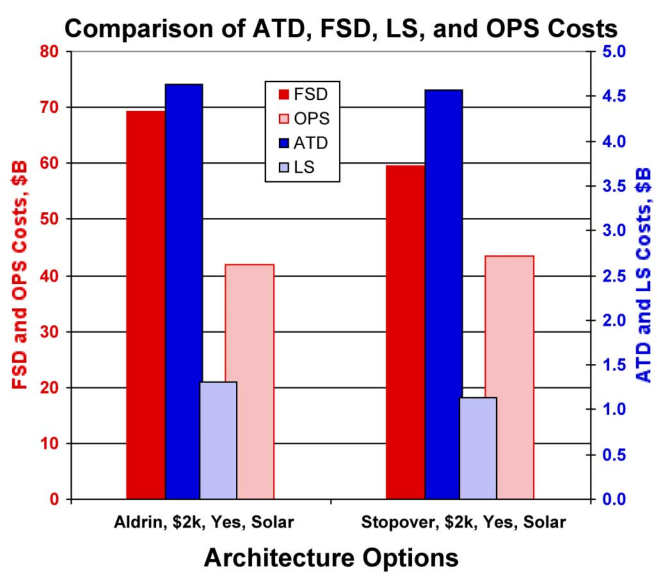


Figure 12 Comparison of Cost Elements between the Aldrin and Stopover Architectures

SUMMARY

There are a number of choices in future Mars exploration planning. One can follow the Apollo expedition approach, characterized as "flags and footprints", that has resulted in an absence of human exploration of the Moon for over a quarter century. Or one can develop an evolutionary approach to Mars exploration by establishing and using elements of the infrastructure needed to eventually maintain a human presence on Mars. The first choice will get humans to Mars but in the process we may damage political and public support to the extent that, like Apollo, Mars exploration is eventually abandoned. The latter choice lays the foundation for low life-cycle cost transportation that has a much higher probability of sustained political and public support.

If we know what systems and vehicles will be required in the future to support a Mars transportation architecture, the steps to the development of this infrastructure can be constructed including the long-range planning and costing, advanced technology development, advanced system development and flight-testing. Intermediate vehicle or surface systems can begin to be used, perhaps for lunar or Phobos exploration, as they are developed with the knowledge that their efficiency is driven not necessarily by their immediate use but by their eventual application in the overall infrastructure.

A key example of providing a context for future technology development is the assessment of the need for and development cost of nuclear power generation systems in a future architecture. If such systems are not absolutely required, or result in higher life-cycle costs than solar systems, as discussed above, then we can save considerable time and precious resources by not pursing the nuclear option.

A key question is the need for ISRU systems and whether they are cost effective. The answer to the question will require a better understanding of the future of launch costs. If launch costs can really be reduced to the order of $2k/kg the argument for ISRU may be less strong than if these costs are really $10k/kg. In addition, how ISRU fits into future near-Earth operations needs to be evaluated in order to determine if the development, and a portion of the operations costs, can be amortized beyond the Earth to Mars transportation needs.

The concepts envisioned by this systems architecture have a potential role to play in the expedition phase of Mars exploration. The application of these orbit and systems concepts in the expedition phase of Mars exploration may serve to reduce overall mission development costs and improve overall mission reliability and safety. Once launched into cycling orbits, Astrotels can orbit indefinitely as long as they are periodically maintained, improved and supplied with orbit correction propellants. In addition, the result of embracing such a mission concept early in an expedition phase means that a permanent inhabitation phase of Mars is closer. 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 have a role to play in the expedition phase of human Mars exploration.

By establishing the goal of developing a Mars transportation architecture, planning and mission context is provided for robotic and human space exploration. Without this framework, we may expend valuable resources on extraneous technologies and dead-end system developments.

ACKNOWLEDGMENTS

We would like to acknowledge the support of the NASA Institute for Advanced Concepts through their Universities Space Research Association Contracts Nos. 07600-49 and 07600-59. In addition, we acknowledge the efforts of those who participated in this work including Dr. Kim M. Aaron, Dale R. Burger, Kristin L. Gates and Brenda Wistor-Linfield of Global Aerospace Corporation; Alan L. Friedlander of Science Applications International Corporation; and Professors Robert Knecht, Dave Munoz, Ron Miller, and Colin Wolden along with many of their students at the Colorado School of Mines.

REFERENCES

Aldrin, E. E., "Cyclic trajectory concepts. SAIC presentation to the Interplanetary Rapid Transit Study Meeting," Jet Propulsion Laboratory October 28, 1985.

Hoffman, S. Friedlander, A. and Nock, K., "Transportation Performance Comparison for a Sustained Manned Mars Base," AIAA Paper No. 86-2016-CP, AIAA/AAS Astrodynamics Conference, Williamsburg, Va (1986).

Johnson, L., King, R. H., and Duke, M., "Extraterrestrial In Situ Resource Systems Concepts Development," Final Report submitted to Global Aerospace Corporation by the Center for Commercial Applications of Combustion in Space, Colorado School of Mines, February 25, 2002.

Nock, K. T. and Friedlander, A., "Elements of a Mars Transportation System," Acta Astronautica, 15, No. 6/7, 505-522 (1987).

Nock, K., Frequent, "Fast Trips To and From Mars Via Astrotels," paper at Space Studies Institute/Princeton Conference on Space Manufacturing: High Frontier Conference, Princeton University, May 2001.

Penzo, P. A. and Nock, K. T., "Hyperbolic Rendezvous for Earth-Mars Cycler Missions," paper AAS-02-162, AAS/AIAA Space Flight Mechanics Meeting, San Antonio, TX, January 2002a.

Penzo, P. A., "Earth-Mars Transportation Using Stop-Over Cyclers," AIAA Astrodynamics Conference paper, Monterey, CA, August 2002b.

Scott, C. D., et al., "Design Study of an Integrated Aerobraking Orbital Transfer Vehicle," NASA TM 58264, March 1985.