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ELEMENTS OF A MARS TRANSPORTATION SYSTEM†

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Abstract—Earth to Mars transportation requirements are derived for a permanent Mars base of 20 people operating in the 2035 time frame. In order to satisfy these requirements, various transportation modes are developed assuming an existing space infrastructure including propellant tankers, crew and consumable transfer vehicles, orbital facilities and extraterrestrial propellant factories. These transportation modes are compared with respect to total propellant requirements, number of vehicles required, flight times, frequency of opportunity and several other characteristics. Directions for further studies and analysis are indicated.

1. INTRODUCTION

It has been about 15 years since extensive research into interplanetary transportation concepts has been carried out. These early studies primarily focused upon short duration manned expeditions of the Apollo type[1–5]. In the intervening period, new concepts have been identified and developed which may become factors in the design of a future transportation system, including circulating trajectories, libration point staging, the use of tethers, lunar and Mars propellant manufacturing, aerobraking and others. In addition, much more is now known about the effects of the space environments upon man and his machines. These new ingredients have been incorporated into recent studies to determine the potential elements of a Mars transportation system. In addition, the philosophical approach to future manned Mars transportation has evolved from Apollo-like expeditions towards establishment of a sustained Mars base[6,7]. The implication of this new approach means that the first people to visit Mars will begin an era of permanent inhabitation of our neighboring planet.

Recent Mars transportation system studies have been carried out by NASA to identify the range of choices, to begin research into new concepts, and to compare the performance of various options. In addition to the classical minimum energy trajectories, called conjunction transfers, advancements in the understanding of orbital mechanics have produced new kinds of circulating trajectories. Circulating trajectories are orbits between planets which are continuous, repeatable, and involve hyperbolic flybys of target planets. In circulating or conjunction orbits, large Cycling Astronautical Spaceships for Transplanetary Long-duration Excursions (CASTLEs) can operate between Earth and Mars. CASTLEs provide for many of the comforts of home: protection against space environments, and artificial gravity throughout the long transit times[8]. Another vehicle type, known as Taxis, provide transportation for people and consumables between these spaceships and planets. In the case of circulating orbits, these Taxis use hyperbolic rendezvous techniques to effect transfers. An advantage of CASTLEs on circulating trajectories is that the large system masses required for shielding, life support and artificial gravity are placed onto these orbits only once. Alternatively, an advantage of CASTLEs designed for conjunction transfers is that they can be targeted for bodies other than Mars.

There are several candidates for staging base sites at Earth and Mars. At Earth these include low Earth orbit, geosynchronous orbit, Earth–Moon and Earth–Sun libration points, and cycling orbits between the Earth and the Moon. At Mars the candidates include Mars–Sun libration points, Phobos orbit and high elliptical orbits. An important factor in comparing transportation nodes is the source of propellants. The use of lunar oxygen and Phobos hydrogen and oxygen strongly point to locating node points near these resources.

Crew loading and tours of duty have been studied for various transportation modes. Propellant requirements have been estimated for several transportation scenarios and the propellant manufacturing rates for extraterrestrial sources have been established. These requirements have implications for the supporting infrastructure on the Moon and Phobos. In the future, the choice of a cost-effective Mars trans-

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portation system will ultimately depend upon a number of factors including: (1) availability and cost of extraterrestrial resources; (2) Mars base size; (3) crew scheduling requirements; (4) cost of space infrastructure; and (5) buildup requirements.

A cornerstone assumption of this work is the existence of a permanent manned Mars base of 50 years into the future—2035. A concept of this base is described in sufficient detail in order to extract Earth-to-Mars transportation requirements including transport of people and high value cargo. The method by which this base is established, while of great interest, is not examined here. In fact, a future Mars base and the meeting of its transportation requirements can be viewed as a two point boundary value problem; once the end points are establised—the world of 1986 and our vision of 2035—many solutions to achieving the end points can be created. The "optimum" solutions will depend on the level of international commitment to such a project, overall cost-effectiveness of the various solutions and future technology developments. The development of potential pathways between these boundary conditions are beyond the scope of this work.

An existing space infrastructure is described which can support a Mars transportation system. Elements of this infrastructure include extraterrestrial propellant manufacturing capability on the Moon, Mars and Phobos; orbital spaceports at Earth and Mars and propellant tankers and crew and consumable transfer vehicles which operate between the various elements. This space infrastructure is described in enough detail in order to establish its capability of supporting a Mars transportation system. In particular, rationale, assumptions and requirements for interplanetary CASTLE vehicles are discussed.

Two basic classes of trajectory options are circulating and stopover orbits. Of the circulating type, two are discussed in detail: Versatile International Station for Interplanetary Transport (VISIT) orbits and Up/Down Escalator orbits. VISIT orbits are commensurate and tangent to the orbits of Earth and Mars and provide repeated returns to Earth and Mars every few years. Up/Down Escalators use the gravity assist concept to rotate a heliocentric orbit to pick up Earth and Mars flybys every 2 1/7 years; the synodic period of these planets. The only class of stopover trajectory examined in detail is the classical, minimum energy, conjunction transfers. If transient time becomes more important than launch energy, other stopover trajectory types should be considered.

Three basic transportation modes and one variant are developed based upon these trajectory types. Transportation velocity change, delta-V requirements, are calculated for three transportation modes with various assumptions including: the end points at Earth and Mars, flyby altitude limits, Taxi transit time and others. Total propellant requirements are determined over a complete 15 year cycle of Earth and Mars opportunities. Here, total propellant includes all propellants required in order to transport crews, consumable and propellants from their sources to the transportation nodes, and onto the CASTLEs. Excluded are Earth launch propellants required to place payloads in Low Earth Orbit (LEO).

The sensitivities of propellant requirements are calculated for differences in crew Taxi module, consumable, and refurbishment masses. In addition, the total propellant requirements are also calculated assuming the use of Phobos hydrogen and oxygen in place of Earth and lunar sources. The characteristics, including propellant requirements, of the various transportation modes are compared and the extraterrestrial propellant manufacturing rates computed. It is suggested that factors other than propellant requirements may be just as important—or perhaps more important—to deciding on the "best" transportation mode. These other factors include: Number of CASTLEs, tours of duty, Mars staytime, frequency of opportunity, support-crew to Mars-base-crew ratio and others.

Finally, as this work just scratches the surface of the overall problem of Mars bases and transportation sysems, directions for future studies and analysis are suggested. In particular two areas to focus on in any future work ought to be the analysis of orbital mechanics related to orbital staging bases and the effect of future advancements in the emerging technologies. In addition it is suggested that future transportation mode comparisons should include cost aspects, accounting also for launch to LEO requirements.

2. MARS BASE: 2035

The era of permanent habitation of Mars commences about 50 years from the present time in this scenario. It follows a relatively brief period of early manned exploration of the planet and its satellites Phobos and Deimos, and then an extended period of buildup to the point of a viable, nearly self-sufficient outpost in the Martian system. A steady-state operation of this Mars base is assumed for an interval of at least 15 years, after which there might occur a new evolutionary era of Mars colonization. Since this paper focuses on the transportation requirements of crew rotations in support of the steady-state Mars base, it is appropriate here to present an overview and brief description of the assumed base activities and infrastructure[9,10].

The level of capability envisioned would support significant surface activities in the areas of science exploration, resource surveys, life cycle maintenance, propellant production, and materials processing and fabrication. These activities, which take place at one or two fixed-site facilities on Mars and on distant traverses from base, will require a high degree of mobility, appropriate levels of automation with efficient man-machine interfaces, and crews that combine the need for individual specialization with job sharing abilities. An artist illustration of the Mars base is shown in Fig. 1.

A crew complement averaging 20 persons on the Martian surface is believed to be required to 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 transportation mode (trajectory option). In addition to the Mars surface facilities, the overall Mars base infrastructure includes a liquid oxygen/hydrogen propellant production plant on Phobos which is man-tended, a manned spaceport near Phobos serving as a work station and transportation staging node, and several shuttle transports operating between the Martin surface and the spaceport as needed. A crew complement averaging 6 persons is the assumed requirement for the spaceport facility. Both the spaceport and Mars surface are permanently inhabited in this scenario which provides staggered crew rotations and, thus, overlap between "experienced" and "fresh" personnel.

Manned scientific research on Mars will feature activities that require spontaneous observation, integration and interpretation of data, and, above all, adaptation to new findings. The ability to emplace, calibrate, and repair science instruments is also important. Significant accomplishment in such science disciplines as geology, geochemistry, geophysics, and atmospheric phenomena would have already occurred during earlier missions. The era of permanent inhabitation offers the opportunity to greatly extend these investigations in both spatial region and time duration. A shift in emphasis to applied sciences can be expected, i.e. those areas that impact long-term survival on Mars. Thus, exploration and research will be performed to verify the existence and utilization of certain resources (e.g. subsurface permafrost) or avoidance of hazards (e.g. superoxides), and to understand fully the past record and current state of planet biology, climatology, incident physics (particle/radiation influx), and comparative planetology and, perhaps, to conduct "change" experiments in carefully selected areas.

Fig. 1. Artist's conception of a Mars base *c.* 2035 A.D.

Self-sufficiency and resources utilization are the major focus of the Mars base and dominate much of the crew activity and attention. The environmental control and life support system will be regenerative to a large degree but not entirely closed. Supplies of oxygen, water and carbon dioxide can be extracted from the soil and atmosphere. Plants of different varieties will be grown in greenhouse enclosures while other types of food will be produced using such methods as aquaculture. The operational objective is a bioregenerative system with minimal replenishment from Earth (except, perhaps, for niceties such as sirloin steak). This same objective is true for propellant resources used for long traverse mobility on the surface and in the atmosphere, for rocket vehicle transportation between Mars base and Phobos spaceport, and for refueling the transportation vehicle systems used in departure to Earth return. Thus, *in situ* propellant production facilities yielding oxygen/methane and oxygen/hydrogen propellants will exist on Mars and Phobos.

Table 1 lists the various facilities and system elements comprising the Mars base infrastructure together with estimates of their mass requirements. Total mass at the time of steady-state operation is almost 450 metric tons. Habitat and laboratory modules brought from Earth will be of the standard LEO Space Station type, while surface base growth can be accomplished using *in situ* Martian materials. These modules are buried in Martian soil for protection from ionizing radiation and large solar flare events. Pressurized volume will be created using tunneling and sealing techniques. The compressed carbon dioxide washdown facility is employed to remove the potentially toxic surface dust from personnel and equipment before entering the pressurized areas.

Habitat power is provided by moderate-size, nuclear reactor generators of the SP-100 type. The manufacturing facilities will have their own independent nuclear power sources. The atmosphere reduction facility will produce oxygen, hydrogen, water, air fertilizer, methane, and other chemicals and energy storage compounds. The materials processing and refining facility will also produce water and fuels as well as metals, glass, cement and other construction materials.

Table 1. Mars base infrastructure

System elements	Unit mass (mt)	No. of units	Element mass (mt)
1. Life Critical Systems			
Habitat	17.1	4	68.4
Washdown facility	0.9	2	1.8
2. Mission Support Systems			
Nuclear power source (25 kWe)	1.7	5	8.5
TDRS/survey/science satellite	2.3	5	11.5
Suitup/maintenance facility	1.8	2	3.6
Pressurized transporter/dozer	9.1	3	27.3
Apollo-type rover	0.9	6	5.4
Inflatable shelter w/airlock	0.5	10	5.0
Autonomous/teleop. vehicle	0.5	11	5.5
Mars airplane	0.3	3	0.9
Crane	5.0	2	10.0
Trailer	2.0	2	4.0
3. Science and Exploration Systems			
Base lab	13.6	2	27.2
Mobile lab	9.1	3	27.3
100 m base drill	2.3	1	2.3
10 m mobile drill	0.1	3	0.3
Weather/survey satellite	2.3	3	6.9
Weather station	0.5	5	2.5
4. Resources Utilization Systems			
Atmos. reduction pilot plant	8.0	1	8.0
Atmos. reduction fac. (Phase 1)	60.0	1	60.0
Atmos. reduction fac. (Phase 2)	50.0	1	50.0
Matl. proc./ref. pilot plant	6.0	1	6.0
Matl. proc./ref. fac. (Phase 1)	50.0	1	50.0
Matl. proc./ref. fac. (Phase 2)	25.0	1	25.0
Boring/mining equipment	6.0	3	18.0
Food production pilot plant	2.0	1	2.0
Food production facility	5.0	2	10.0
			447.4

Two types of large surface mobility vehicles are included. For long range, long duration traverses, a pressurized transporter will tow a lab module to and from remote temporary sites for purposes of science exploration and resource assessments. This vehicle can also be equipped with a detachable bulldozer blade when used for base construction tasks. Shorter traverses will be made in an Apollo-type rover with portable life support including an inflatable shelter for purposes of rest and environmental protection. An automated Mars airplane is used for long range reconnaissance and exploration such as performing aerial surveys, delivering small instrument packages to remote land sites, collecting samples, and performing atmospheric soundings. Such an airplane would weigh 300 kg including fuel and payload, and be capable of per sortie ranges from 3000 to 10,000 km, depending on its VTOL assist capabilities.

In summary, the Mars base infrastructure described above should prove quite satisfactory and capable as the first permanent outpost on Mars and a stepping stone to extended colonization should this be desirable. As stated in the introductory remarks, the means of emplacing this base initially, or its equipment resupply from Earth, is outside the scope of this study. With this Mars base as a given assumption, the remainder of this paper will address the requirements of the transportation infrastructure (and its various options) that is needed to bring personnel to and from Mars on a sustained basis of crew rotations.

3. TRANSPORTATION SYSTEM INFRASTRUCTURE

The transportation requirements which have been developed, including crew transfer and resupply, relate only to the maintenance of the Mars base. Included, however, are the requirements for sustaining the Mars spaceport and the interplanetary CASTLEs. The infrastructure elements needed to support these requirements and the assumptions leading up to them will each be discussed in turn in the following paragraphs.

3.1. Extraterrestrial propellants

A major assumption of this study, which differentiates it from many of the other manned Mars studies, is the existence, production, and use of extraterrestrial propellants. These propellants are assumed to be manufactured at four sites in the Earth–Mars system: the Earth itself, the Moon, Mars, and finally Phobos.

The Apollo expeditions to the Moon indicated that the Moon was a poor source of hydrogen. As a result, a primary assumption is that all hydrogen used in Earth–Moon space must be brought from the surface of the Earth to low Earth orbit by an unspecified heavy lift launch vehicle. The propellant required for Earth launch is not counted in the performance total, but the propellant to move the hydrogen from LEO to the spaceport is included.

The same Apollo expeditions determined that the Moon was a rich source of oxygen in addition to other elements which could serve a wide variety of applications in space. Many recent studies which discuss a return to lunar exploration identify the specific activity of mining as one of the major goals with oxygen accounting for a significant fraction of the final products. Due to the lower velocity change needed to place this portion of the infrastructure propellant into Earth–Moon Space (as compared to bringing if from the surface of the Earth), this is assumed to be the location of all oxygen needed by all vehicles operating in this vicinity (i.e. local transporters and CASTLEs).

The third propellant manufacturing site is Phobos (see Fig. 2). The availability of hydrogen and oxygen from water on Phobos is predicated on this satellite being composed of carboneous chondritic material which can contain up to 20%, by weight, water. The Viking Orbiter data indicate that the mean density, spectral reflectance and absolute albedo of Phobos are consistent with it being similar in composition to Type I or II carbonaceous chondrites which can be 5–20% water, by weight[11]. The lack of water on Phobos could cause a significant difference in the transportation infrastructure and comparison results.

One transportation mode option investigates the near total use of Phobos resources. In this option

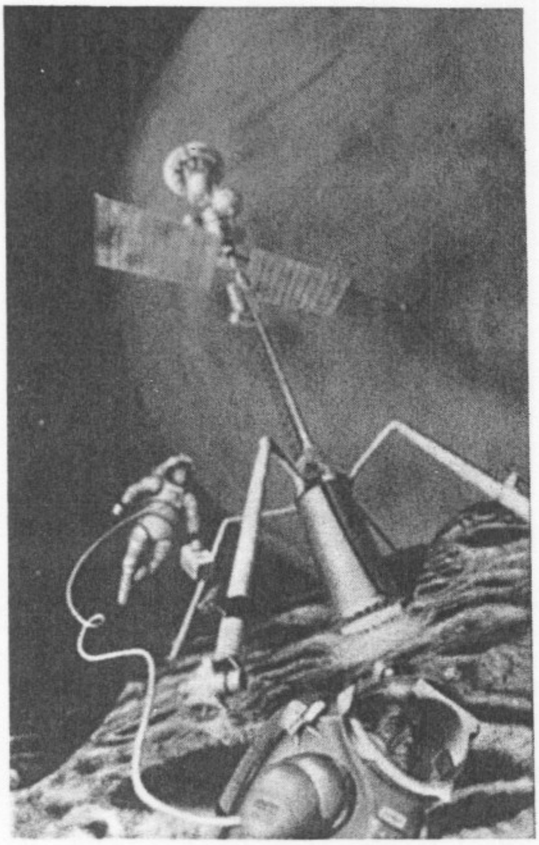

Fig. 2. Phobos propellant plant (courtesy B. Roberts, JSC).

large unmanned Nuclear Electric Propulsion (NEP) vehicles carry propellant from Phobos back to the Earth spaceport. These vehicles could be patterned after the same NEP vehicles which could possibly be key elements of buildup of the Mars infrastructure (see Fig. 3). Round trip flight time requires about 3 years. Such NEP propellant tankers could be analogous to super oil tankers: although taking several months to travel from the oil source to market, a large number of them operating ensure a continuous supply. This NEP tanker would use a 7 MW nuclear reactor along with Magnetoplasma Dynamic (MPD) thrusters operating at a specific impulse of 5000 s at an overall efficiency of 50%. Such a vehicle could return nearly 330 mt of Phobos resources to the Earth every trip.

The last propellant site to be disccussed is Mars itself. Viking Orbiter data indicate that water existed on the surface but what remains is now trapped at the poles. The assumption made here is that sufficient oxygen and hydrogen can be produced on the surface to ferry the base crew to the Mars spaceport where the vehicle will be resupplied with propellant for the return trip.

3.2. Spaceports

There are several candidate sites which can serve as transportation nodes, or locations for staging bases, at Earth and Mars. At Earth these candidates include LEO, geosynchronous orbit, Earth–Moon and Earth–Sun libration points, and cycling orbits between the Earth and the Moon. At Mars the candidates include Mars–Sun libration points, Phobos orbit and highly elliptic orbits. An important factor in comparing spaceport location is the source of propellants. The assumed use of lunar oxygen as well as Phobos oxygen and hydrogen points to locating spaceports near these resources. For the purpose of this comparison study the staging terminals are

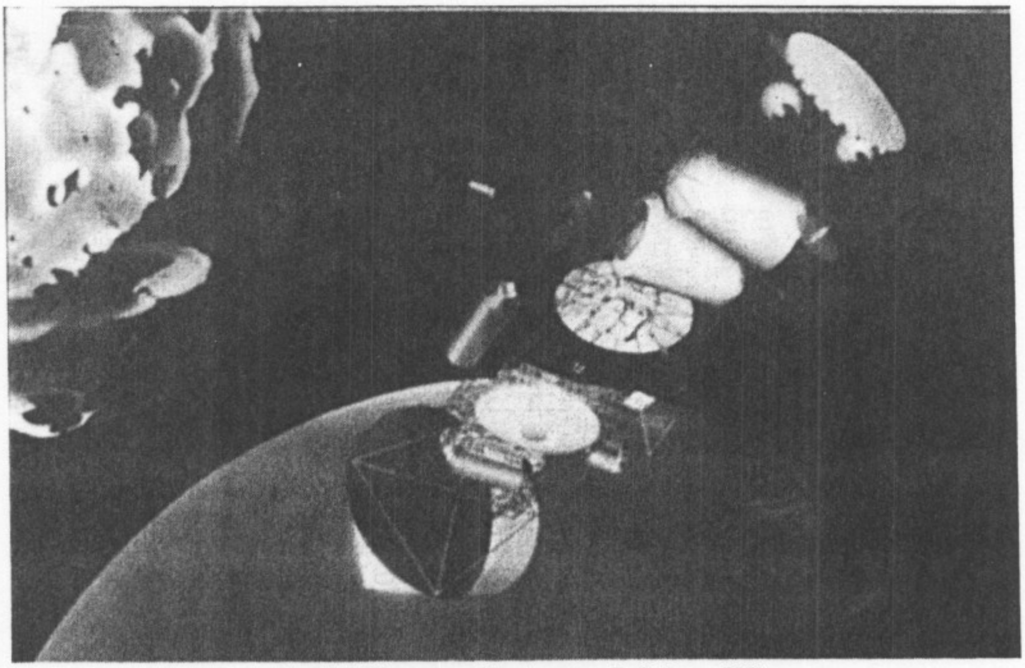

Fig. 3. NEP cargo vehicle (courtesy B. Roberts, JSC).

located at the Earth–Moon L_1 libration point and co-orbiting with Phobos at Mars. The selection of these terminals is preliminary and not the result of a detailed comparison study with other possible alternatives.

The criteria used to select the L_1 point as a spaceport location were based on an attempt to minimize the delta-V requirements for all transportation elements operating in Earth–Moon space. Table 2 shows these delta-V values for the options examined. The principal contenders are the L_1 point and an Earth–Moon cycler. The L_1 point was selected due to its natural stationkeeping characteristics and the delta-V penalty imposed on the cycler during non-ideal launch geometry situations. The Mars spaceport must support both Phobos operations and CASTLE-related activities. As a result, this facility is located in close proximity to Phobos (co-orbiting Mars) to serve in this dual function. These spaceports serve as refueling depots and maintenance facilities for all transportation elements in their vicinity, including CASTLEs. In the case of the cycling CASTLEs, which never achieve orbit at either Earth or Mars, all propellant and maintenance items are transported to these vehicles as part of the cargo carried with the crew during hyperbolic rendezvous.

Both spaceport facilities are similar in configuration, possessing a spinning section to provide artificial gravity for the crew and a non-spinning section for a variety of activities. These activities could include support for scientific investigation, zero gravity construction, and spacecraft maintenance. While these facilities carry out other duties not related to the transportation infrastructure support (this is especially true at L_1), their major function with regard to this investigation is to act as a storage depot for propellants and consumables. The cryogenic tank farm, with its necessary support systems, becomes a substantial facility at both locations as traffic demands grow. Figure 4 illustrates the Mars spaceport.

3.3. *Mars base*

The Mars base itself is assumed to be developed to the point where it has the capability of supporting significant surface operations in the areas of science, resource surveys, life cycle maintenance, propellant production, and materials processing and fabrication with the assumption of significant levels of automation and job sharing. This level of activity is assumed to require a crew with an average size of 20, although the total population could fluctuate from approximately 10 to 30 depending on the phase of the crew rotation cycle dictated by the transportation option. Each crew member is assumed to serve a tour of duty lasting approximately five to six years, Earth departure to Earth return. The base will be supported by a closed life cycle capable of generating consumables to support not only the base but the partial needs of the CASTLE and the Mars spaceport. This eliminates the need to bring significant quantities of consumable mass from Earth at each opportunity to support the Mars base and CASTLE needs on the return trip. As mentioned above, the base is assumed to be capable of generating enough oxygen and hydrogen to supply the propellant requirements of a shuttle transporting a portion of the surface crew to Phobos; the vehicle will be resupplied with Phobos propellant for the return trip.

3.4. *Transport vehicles*

Six vehicle types are required by the transportation infrastructure to accomplish all of the functions in all of the scenarios. Two of the vehicle types are based in Earth–Moon space including a liquid hydrogen tanker operating between L_1 and LEO as well as a liquid oxygen tanker operating between L_1 and the lunar surface. At Mars, two vehicle types are also needed including a tanker/personnel transporter based at the Mars spaceport and a shuttle vehicle operating between the surface of Mars and the Mars spaceport. The fifth vehicle is used only in the cycling orbit transfer cases. This vehicle is referred to as a Taxi since its basic purpose is to ferry crews to and from the CASTLE on its hyperbolic flyby of Mars and Earth. The last vehicle common to all scenarios is the CASTLE which is used to transport crews from one planet to the other. Depending on the orbit transfer option selected, there may be slight variations in the configuration, mass, and operation of this vehicle. The one set of features which is common to all of these vehicles is the characteristics of the propulsion system. All engines are assumed to use hydrogen and oxygen as propellants (at a mixture ratio of 7) and can perform at a specific impulse of 460 s.

Table 2. Delta-V requirements for staging in Earth–Moon space

Staging location	Trans-Mars(1) injection (m/s)	Transport(2) from LEO (m/s)	Transport from(3) lunar surface (m/s)
LEO	4470	—	2670
GEO	3540	3820	3520
Earth–Moon L_1	2050	3670	2510
Earth–Moon cycler	1408	3058	2550
Lunar orbit	2230	3880	1730
Lunar surface	3960	5610	—

(1) Escape energy $C = 30\ (\mathrm{km/s})^2$ typical of Up Escalator transport mode assumes ideal geometry and final injection burn at 6878 km perigee.
(2) LH_2 from Earth.
(3) LOX from Moon.

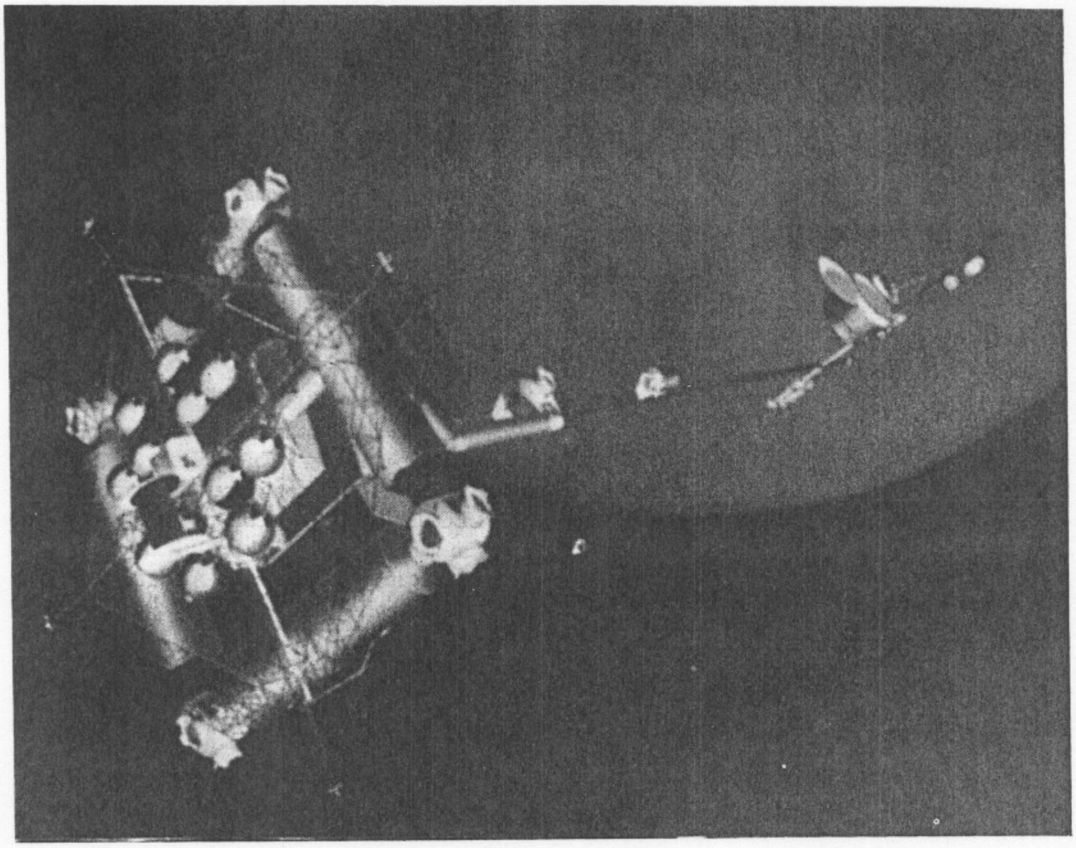

Fig. 4. Mars spaceport (courtesy B. Roberts, JSC).

3.5. *Hydrogen tanker*

The first of these vehicles is the liquid hydrogen (LH_2) tanker which moves this component of propellant from LEO to L_1. A personnel module can be added to this vehicle to allow it to carry up to seven crew members from LEO to L_1 for eventual transfer to the CASTLE. The last function of this spacecraft is to act as part of the escape stage for the CASTLE in the conjunction class mission. The characteristics of this tanker are based on aerobraked orbital transfer vehicle (OTV) studies currently in progress at NASA/MSFC and NASA/JSC [19]. This vehicle has a dry mass of 7000 kg, which includes all structure, tankage, engines, and thermal protection. The tanks for this configuration have an internal propellant capacity of 42,000 kg.

With these characteristics, this tanker can lift 18,000 kg of hydrogen to L_1. This assumes that the tanker receives its supply of liquid oxygen (LOX) exclusively from L_1, using the LOX manufactured on the Moon. The crew module mass is assumed to be 10,000 kg which accounts for the crew, internal accommodation, a partially closed life support system (for air and water), structure and consumables for the three day flight to L_1 (see Fig. 5). When used as part of the Earth escape system, four of these tankers are linked to each other and to the conjunction CASTLE. Aerobraking is used to bring these tankers back to L_1 where they are reloaded with propellant for the return flight to LEO.

3.6. *Lunar LOX tanker*

The lunar tanker requires a new design estimate since no detailed studies similar to the LEO tanker have been completed. Preliminary design work by Eagle Engineering in 1985 under contract to NASA/JSC has led to a concept which is applicable in this situation. The sole function of this unmanned vehicle is to lift LOX from the surface of the Moon to L_1. The basic vehicle has a dry mass of 8500 kg, which includes the structure, landing gear, tankage, and engines. The engine cluster is assumed to have a thrust level of 266,000 N which provides a sufficient thrust to weight ratio to minimize the finite burn gravity losses at liftoff and return. With a maximum propellant load capacity of 50,000 kg this vehicle is able to lift 25,000 kg of LOX to L_1. In an assumption similar to the LEO tanker, this vehicle is resupplied with LH_2 for its own propulsion needs from the supply maintained at L_1.

3.7. *Mars OTVs*

At Mars the focus of most of the transportation activity will be at the Mars spaceport which is in close proximity to the Phobos propellant production facility. This spaceport serves as the base for a set of

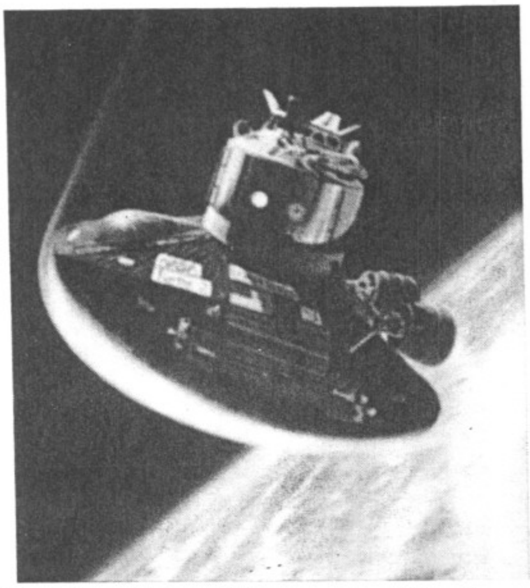

Fig. 5. Example L_1 to LEO transporter vehicle with aerobrake assist (courtesy B. Roberts, JSC).

four aerobraked OTVs identical in configuration to those based at LEO. The function of these OTVs differs slightly depending on the flight mode under consideration. For conjunction missions, these vehicles transport crew to and from CASTLEs which are parked in highly elliptical orbits. In addition, these spacecraft also resupply consumables and trajectory correction propellant to the CASTLE for the return flight to Earth, as well as providing the escape delta-V as was done at L_1. For circulating orbits, these vehicles provide the Taxis with their initial delta-V for escape from Mars and rendezvous with the CASTLE.

3.8. *Mars shuttle*

A shuttle between the surface of Mars and the Mars spaceport facility is also accounted for in this analysis to provide this necessary portion of the infrastructure. As with the lunar tanker, Eagle Engineering in 1985 has examined this problem and has developed a preliminary concept. Using this source of information and some of the same scaling assumptions applied to the lunar tanker (with suitable modifications for items such as re-entry shielding), this vehicle is estimated to have a dry mass of 17,900 kg and a propellant capacity of 50,000 kg. This propellant is supplied by the Mars surface production facility for the flight to Phobos. On return, a smaller amount of propellant is supplied by Phobos for the deorbit and terminal descent delta-Vs. (See Fig. 6.)

3.9. *Taxis*

The Taxi vehicle is only used in the cycling orbit transportation modes. This vehicle has the same mass, propellant and configuration characteristics as the LEO tanker. Two methods are used for those cases in which the escape delta-V is too high for the propellant capacity of the Taxi. At Earth, additional, expendable tankage is added to the vehicle to complete the excess delta-V. At Mars the OTVs used to service the CASTLE in the conjunction case are used here to provide the initial push for the Taxis. In some of the escalator orbit cases even this is not sufficient to escape Mars and rendezvous with the CASTLE. For these situations additional, expendable tankage is added to the Taxi/OTV stack.

3.10. *CASTLEs*

The last vehicle to be discussed is the CASTLE, which is used in all options. This vehicle provides all of the long term needs of the crew during its transit to Mars or Earth. This includes a close loop life support system for air and water, an artificial gravity section, and other essential systems (i.e. power, communications, etc.). Again a preliminary concept developed by Eagle Engineering is utilized here with suitable modifications for the types of orbit transfers under consideration. However, these modifications do not affect the basic vehicle function or support to the crew. For both cases the basic vehicle has a dry

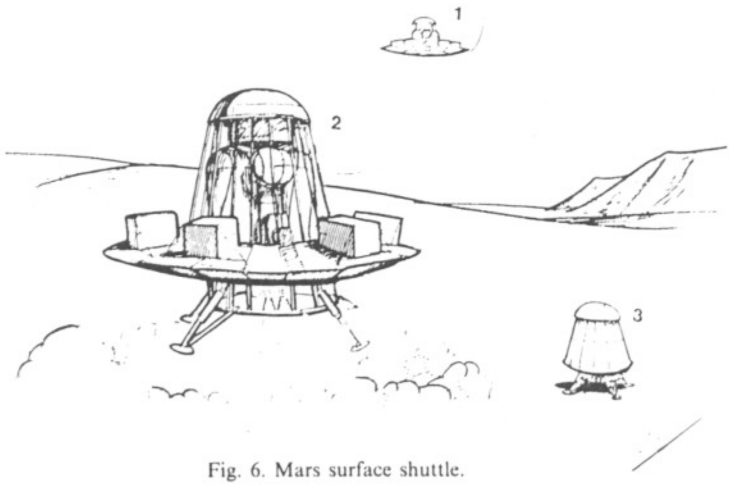

Fig. 6. Mars surface shuttle.

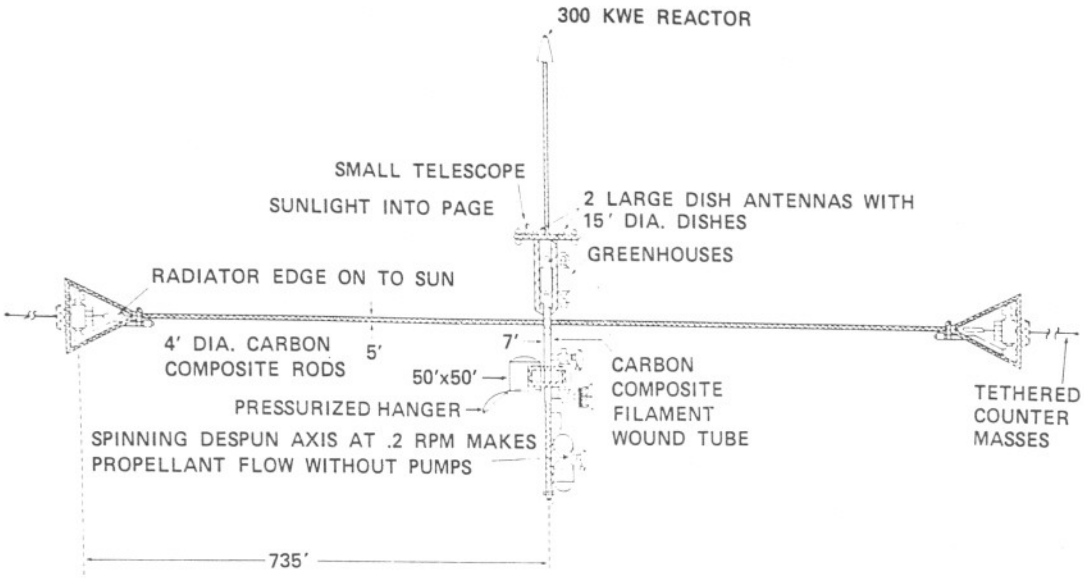

Fig. 7. CASTLE for circulating orbits.

mass of 400,000 kg and can carry a crew of up to 21. When used for the conjunction missions, the CASTLE requires its own propulsion system for capture at both Earth and Mars. This subsystem is sized by the worst case delta-V during the 15 year cycle and has a dry mass of 23,000 kg (tankage and engines). For the cycling cases no large propulsion system is needed; however, maintenance facilities for the Taxis are now required. For the cycling CASTLE, all propulsive maneuvers are carried out by the attached Taxis. Thus, in this configuration the 23,000 kg propulsion system is not included but 60,000 kg for a pressurized hangar and other maintenance facilities has been added, by Eagle Engineering in the 1985 studies, to bring the total CASTLE mass to 460,000 kg. Figure 7 illustrates this version of the CASTLE which has two crew decks on opposite ends.

A key assumption in Eagle Engineering's design of the CASTLE was the requirement to maintain a 1/3 to 1 *g* gravity level for a maximum rotation rate of only 2 rpm: hence the large dimensions of this vehicle. Reducing *g*-level to 1/3 *g* is accomplished by reeling out counter weights on tethers at each end, thus lowering rotation rate. The equipment at the spin axis includes docking facilities, pressurized hanger, nuclear reactor and greenhouses; all of which are despun on near-frictionless bearings. Transfer between the 1-*g* crew decks and the 0-*g* spin axis is accomplished by means of small pressurized elevators. A key element of the CASTLE is the solar flare storm shelters located in the 1-*g* crew decks.

One other consideration which must be taken into account for this vehicle is that it never stops at Earth or Mars for maintenance or overhaul of its own systems. For this reason it has been assumed that 35% of the basic CASTLE mass must be delivered to the vehicle over the course of the 15 year cycle (divided equally over each access from Earth) to account for these needs. For the circulating CASTLEs, during the period of time on the circulating orbit when the Mars surface crew is not in transit, some on board personnel are required even with advanced forms of automation. It has been assumed that six crew members (three shifts of eight hours duration with two crew members per shift) are sufficient to accomplish this task. This is relaxed to a two member crew during the brief period of time when crews are in transit during Earth or Mars flybys. Thus an additional requirement to change this crew and supply them with consumables must be levied on the circulation orbit cases.

Table 3 summarizes the major characteristics of these transportation infrastructure vehicles. With this

Table 3. Assumed transport vehicle characteristics

- All maneuvers with LOX/LH_2, $I_{SP} = 460$ s, 7:1 mixture ratio
- CASTLE-resident propulsion inerts = 10% of maximum propellant loading

● Transportation element	Max. propellant loading (mt)	Total inerts including crew/cargo modules (mt)	Auxiliary tanks for propulsion
Lunar-L_1 tanker	50	8.5	No
LEO-L_1 tanker/transporter	42	17	No
Taxi	42	17	No
Phobos-based OTV	42	7	Yes
Mars–Phobos shuttle	50	17.9	No

- Auxiliary tank inerts = 10% of maximum propellant loading complement of spacecraft, all assumptions are now in place or determining the propellant requirements for each of the orbit transfer options.

4. TRANSPORTATION MODES

Transportation system performance in support of a permanent Mars base is strongly related to the type of trajectory flown between the Earth and Mars terminals. Flight time and velocity impulse characteristics of the trajectory determine the transfer logistics and the propulsion requirements of the entire transportation concept. In this study, three trajectory options are investigated and compared on the basis of their performance impact as measured by the total amount of propellant used over a 15-year transportation cycle. The first option is the traditional, minimum-energy, round-trip mission with a long stopover at Mars, commonly called a conjunction class transfer. The second and third options belong to the family of circulating (non-stopover) trajectories which repeatedly encounter both Earth and Mars during which times there are departures from and access to the heliocentric flight paths. For convenience in designation, the two different circulating modes are termed VISIT orbits and Up/Down Escalator orbits. Figures 8, 9 and 10 illustrate the various trajectory profiles which are briefly described below (see [12] for a more complete description).

The typical conjunction class round trip is characterized by near-Hohmann type transfer segments between the planets with low launch energy (C_3 between 9 and 16 km^2/s^2) and low values of hyperbolic velocity at Mars arrival/departure and Earth return (V-infinity between 2.5 and 4.0 km/s). Parameter variations are due to the fact that Earth and Mars are not exactly in circular, coplanar orbits. Launch opportunities occur every 2 1/7 years comprising a closely repeating 15 year cycle. The Earth-to-Mars transit time varies between 200 and 350 days, the stopover time varies between 330 and 520 days, and the Mars-to-Earth return varies between 190 and 360 days. The total round trip time is fairly constant at 945–995 days, or about 2.7 years, on average.

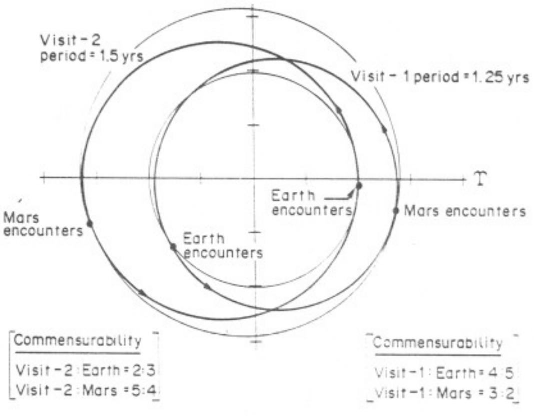

Fig. 9. VISIT orbits.

The VISIT type of circulating trajectory, first proposed by Niehoff[13] evolved from consideration of a class of periodic orbits which might display low relative velocities at both Earth and Mars encounters. For this to occur, the connecting heliocentric paths are nearly tangent to the planetary orbits, i.e. with perihelion close to 1 AU and aphelion placed somewhere near the Mars orbit, between 1.38 and 1.66 AU. The orbit labeled VISIT-1 shown in Fig. 8 has a period of approximately 1.25 years and encounters Mars in the vicinity of its perihelion (1.38 AU). This orbit revolves about the Sun four times while Earth completes five revolutions and Mars completes two revolutions. Hence, the respective 4:5 resonance with Earth and 3:2 resonance with Mars means that Earth encounters will occur approximately once every 5 years and Mars encounters once every 3.75 years. This characteristic motion can be continued with the help of gravity-assisted swingbys of each planet, some close and some very distant. These swingbys adjust for the changing Earth–Mars relative geometry and, with time, effect a small clockwise rotation of the VISIT orbit encounters by several degrees per en-

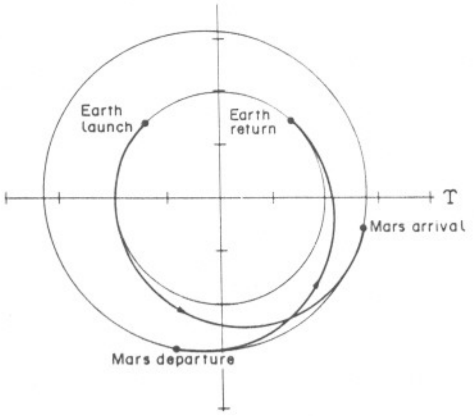

Fig. 8. Conjunction orbits to and from Mars.

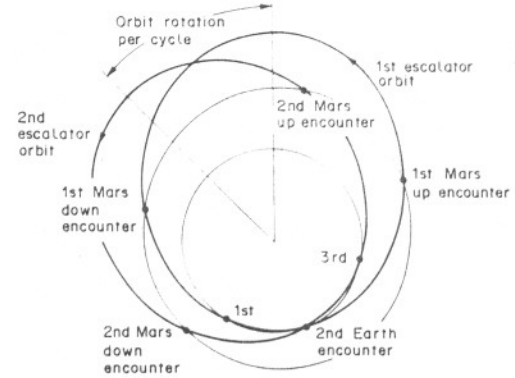

Fig. 10. Up/Down Escalator orbits.

counter. Eventually, the orbit needs to be reset (by "free" gravity assists) to maintain the geometric continuity over many 15 year cycles. The relative velocity characteristics of the VISIT orbit are 4.2–5.2 km/s at Earth encounters and 3.7–3.9 km/s at Mars encounters.

The Up/Down Escalator type of Earth to Mars cycling orbit, first proposed by Aldrin[14], evolved from the desire to have more frequent and regular encounters with both Earth and Mars. These are both elliptical orbits with a 2 1/7 year period and an aphelion point located beyond the orbit radius of Mars. The Up Escalator orbit is oriented so that the Earth to Mars transfer time is approximately six months while the Down Escalator orbit is oriented to allow the same amount of time for the return leg. Since encounter locations on a 15/7 synodic period orbit rotate on average 1/7 of a circle per revolution, there exists a synodic rotation of the apse line equal to 51.4 deg per orbit, which must be effected by either propulsive maneuvers (not desirable) or, to the maximum extent possible, by gravity-assist swingbys of the planets (principally Earth because it is more massive). Given this effective trajectory shaping, both Earth and Mars are encountered sequentially every 2 1/7 years. The encounter speeds at both planets (but principally Mars) are significantly higher than those of VISIT orbits because the 2 1/7 year period transfer orbit has an aphelion distance of about 2.32 AU, thereby crossing the orbit of Mars at steeper (non-tangential) angles. Relative velocities of the Escalator orbit are 5.4–6.2 km/s at Earth and 6.1–11.7 km/s at Mars.

Transportation delta-V requirements are summarized in Table 4 for each of the three interplanetary trajectory options. These data were calculated assuming that the launch staging facility is located at the L_1 point of the Earth–Moon system, and that the injection scenario involves several propulsive maneuvers with the last injection burn occurring at 500 km altitude perigee. L_1 based OTV boosters are utilized to inject the large interplanetary vehicle on the conjunction transfer to Mars. Similarly, OTV boosters based at the Mars spaceport perform the injection onto the Earth return transfer. The conjunction mode transport has resident propulsion capability only for the capture maneuvers at Mars and Earth return plus the small midcourse navigation maneuvers. In the circulating mode cases (VISIT and Escalator), the smaller Taxi vehicles, transporting crew and supplies, provide all of the propulsive capability with one exception: the very large delta-Vs for Mars departure associated with the Escalator mode are implemented with the assist of Mars spaceport OTVs. It is also noted that these Taxis utilize a combination of Mars aerocapture and propulsive energy management in transferring from the CASTLE to the Phobos spaceport. Table 4 also lists additional, fixed delta-V requirements of the transportation infrastructure such as the tankers between LEO and L_1 as well as between the Moon and L_1.

The potential benefit of Phobos-derived cryogenic propellants utilized in place of Earth and lunar sources has been examined. In this scenario, the propellants (as payload) would be transported from Phobos to Earth orbit employing an unmanned, nuclear-electric propulsion cargo vehicle. Another type of trajectory option is thus considered for this purpose, namely, a low-thrust flight path between Earth and Mars with spiral escape and capture phases at the planet terminals. The round-trip time of this cargo vehicle is typically about 3 years, including the spiral phases and several months' stopover at Mars. The total delta-V requirement is about 38 km/s, but this is applied at a very high specific impulse of 5000 s.

Several transportation modes have been analyzed, namely: (1) non-circulating Conjunction orbits with 2 CASTLEs, one returning from Mars with the other leaving for Mars; (2) VISIT orbits with 3 CASTLEs and Taxis for hyperbolic rendezvous; (3) Up and Down Escalator orbits with a CASTLE on each type of orbit with Taxis for hyperbolic rendezvous; (4) Down Escalator orbits with a single CASTLE and associated Taxis; and (5) Down Escalator orbit with a single CASTLE mode utilizing only Phobos propellants transported to the Earth spaceport via NEP tankers.

Analysis of transportation modes included calcu-

Table 4. Delta-V requirements for the primary trajectory options, variation over 15 year cycle

Transport mode	Launch from L_1 to Mars	Mars orbit capture	Launch from Mars orbit to Earth	Capture at L_1
Conjunction	1.12–1.47	0.96–1.90	1.03–1.65	1.12–1.44
Visit orbit	1.91–2.54	0.81–1.00	2.36–2.55	1.91–2.54
Up/Down Escalator	2.31–2.74	0.80–2.58	4.09–10.25	2.31–2.74

[a] Conjunction mode: all-propulsive capture to $1.15 \times 7.95\ R_M$ parking orbit (0.75–1.05 km/s Taxi to Phobos). Visit and Escalator Taxis: aero-propulsive capture to Phobos. Additional transportation infrastructure V requirements:

LEO to L_1 tanker/transporter = 4.41 km/s (round trip).
Lunar surface to L_1 tanker = 5.21 km/s (round trip).
Mars to Phobos shuttle = 7.56 km/s (round trip).
Conjunction OTV booster return to L_1 = 1.14–1.49 km/s.
Conjunction OTV booster return to Phobos = 1.54–2.08 km/s.
Escalator midcourse adjustment = 0–1.16 km/s.
Midcourse navigation, all modes = 0.05 kg/s (planet–planet leg).

lation of total propellant requirements, crew flight schedules and vehicle sorties. Fifteen years was selected as the period of time for comparing the results of the analysis. All transportation modes meet the requirements of Mars base and Mars spaceport support. In addition, it is assumed that a minimum crew of 6 is required to maintain the cycling CASTLEs at all times except for the 1–2 week planetary flybys where this constraint is relaxed to a crew of 2. Details of the crew flight schedules and taxi and tanker vehicle sorties are found in [15].

4.1. Conjunction mode

The conjunction mode requires 2 CASTLE's in order to maintain a continuous Mars base crew loading with crew tours of duty of less than 5 years. A typical Mars-bound flight begins with collection of Earth and lunar propellants at the Earth Spaceport at L_1. Just before launch to Mars, three LEO tankers outfitted with crew modules transport the crew of 19 and consumables to the CASTLE at L_1 which has been undergoing refurbishment during its 1.6 year turnaround period.

At injection toward Mars, which is carried out by 4 LEO tankers, the CASTLEs' tanks carry sufficient propellant for minor orbit corrections and propellant for the large orbit insertion maneuver at Mars. After injection the CASTLE is fully deployed and is spun up to provide artificial gravity. At Mars the CASTLE propulsion system places it into an elliptical Mars orbit which is designed especially to take advantage of natural planetary perturbations to align the orbit for CASTLE departure 11 months later. The arrival and departure geometries are illustrated in Fig. 11.

For the return flight, Phobos propellants are loaded on board the CASTLE by OTVs used as tankers. The Mars shuttle transports crew to and from the orbiting CASTLE. As with Earth departure, OTVs provide the injection energy for return to Earth. The total propellant required for this mode over the 15 year period is 30,205 mt for all transportation elements. Most of this propellant is used by the near Earth transport system elements. Mars base crew tours of duty are 4.8 years: 1.6 years in transit on CASTLEs and 3.2 years at the Mars base.

4.2. VISIT mode

The VISIT orbit transportation mode supports the Mars base with three cycling CASTLEs each with a maximum crew capacity of 21. Three CASTLEs required in order to keep the crew tours of duty within reasonable limits, even so, tours approaching 8 years are sometimes required. Crews and consumables transfer to the CASTLEs via Taxis using hyperbolic rendezvous techniques.

As with the conjunction mode, propellant is collected at L_1 for the use of the Taxis and for the small amount of propellant carried to the CASTLEs for

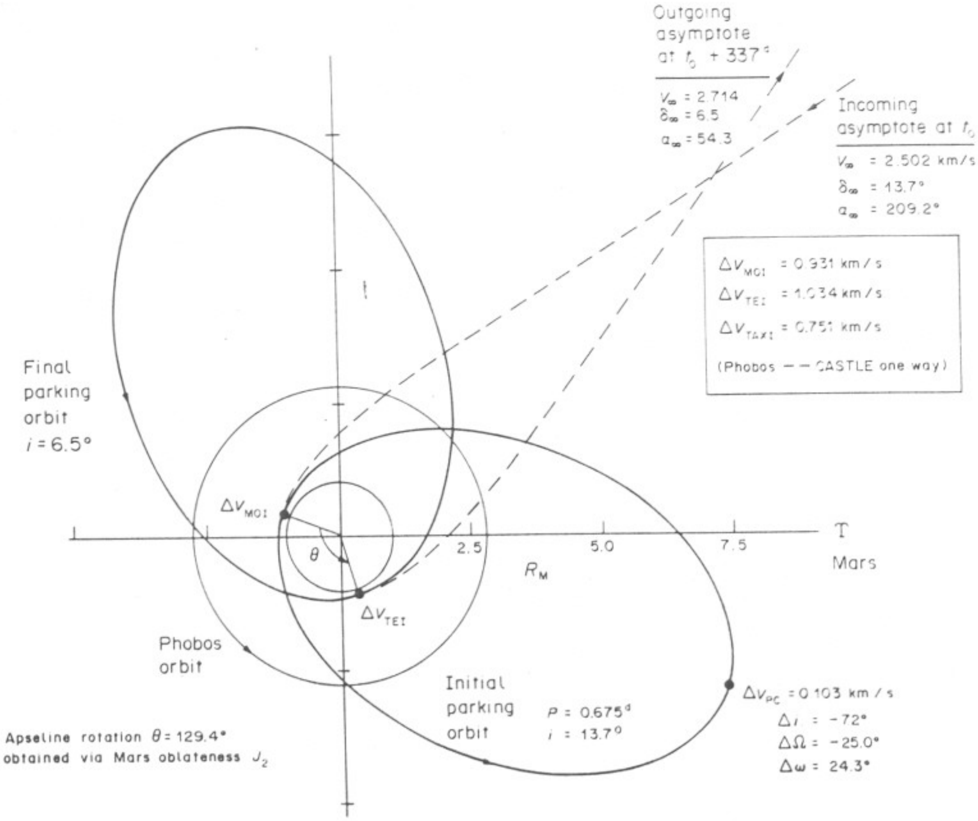

Fig. 11. Mars orbit maneuvers for the conjunction mode CASTLE.

orbit correction propulsion maneuvers. Three Taxis, under refurbishment at L_1 since the arrival of the first Mars base crew, are loaded with a new crew, consumables and CASTLE maintenance items in readiness for departure to the CASTLE. All three Taxis launch from L_1 and arrive and dock at the CASTLE about 1 week later. Months to years later, depending upon VISIT orbit, on the approach to Mars the crews re-enter the Taxis and depart the CASTLE for Mars. At Mars the Taxis use the atmosphere to slow down and orbit, eventually arriving at the Mars spaceport near Phobos. Transfer to the surface base is by the Mars shuttle.

For the return to Earth the sequence is similar except that Mars spaceport OTVs are used to augment the Taxi delta-V capability if it is not sufficient alone to achieve CASTLE rendezvous. Again, use of the atmosphere reduces chemical delta-V requirements upon the return to Earth of the Taxis. Total propellant required for the VISIT mode is 21,500 mt over the 15-year period.

4.3. *Escalator modes*

Two CASTLEs meet the transportation requirements of the Mars base in the Up/Down Escalator mode if the crew tours of duty are limited to 5 years. The use of two CASTLEs on Up and Down Escalator orbits minimizes crew flight time in transit to and from Mars. If tours as long as 6.5 years are allowed, a single escalator orbit CASTLE is sufficient. In the Up/Down Escalator modes, each CASTLEs make 7 round trips in the 15 year period.

The sequence of events for Taxis is very similar to the VISIT mode except that higher escape delta-Vs are required at both Earth and Mars. Jettisonable auxiliary propellant tanks augment the Taxi propulsion capability for Earth launch to CASTLE. At Mars, spaceport OTVs are required to augment the Taxi capability. Occasionally, due to the high delta-Vs departing Mars, auxiliary drop tanks are needed. Figure 12 illustrates a typical Taxi departure from Mars.

On 3 orbits out of 7, for the Up and Down Escalator CASTLEs, moderate delta-V maneuvers are required in order to augment the heliocentric orbit rotation capability of the Earth gravity assists. This delta-V is in addition to small orbit correction maneuvers before and after each planetary flyby. As with the VISIT mode, Taxi propulsion systems provide these propulsive maneuvers, using additional propellant brought to the CASTLE by all Taxis and stored on board until needed.

Overall propellant requirement of the Up/Down Escalator mode for 15 years is 32,830 mt. This requirement exceeds the propellant required by the conjunction mode due to the fact that even though a smaller vehicle (Taxi) is being launched from the Earth and Mars, this vehicle makes twice as many sorties and at a higher per launch delta-V cost. In addition, a large amount of propellant is used for the periodic orbit rotation delta-Vs. An example crew loading schematic and flight schedule of this mode are shown in Figs 13 and 14. A variation of this mode, the single Down Escalator mode was studied. The reduction in propellant to a total of 23,660 mt is paid for by a 1 1/2 year longer tours of duty.

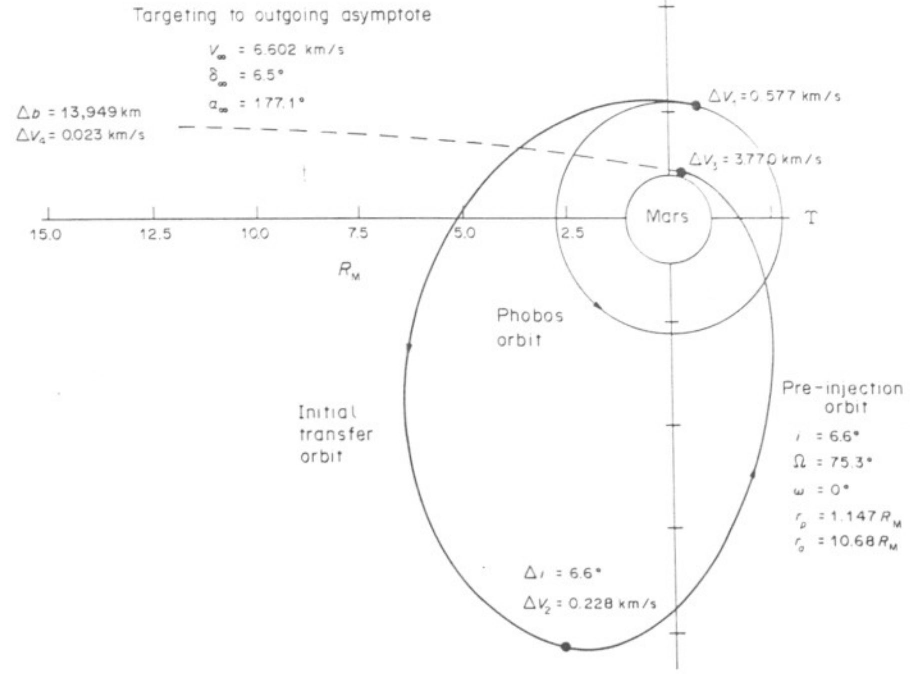

Fig. 12. Typical Taxi departure from Mars toward Down Escalator CASTLE rendezvous.

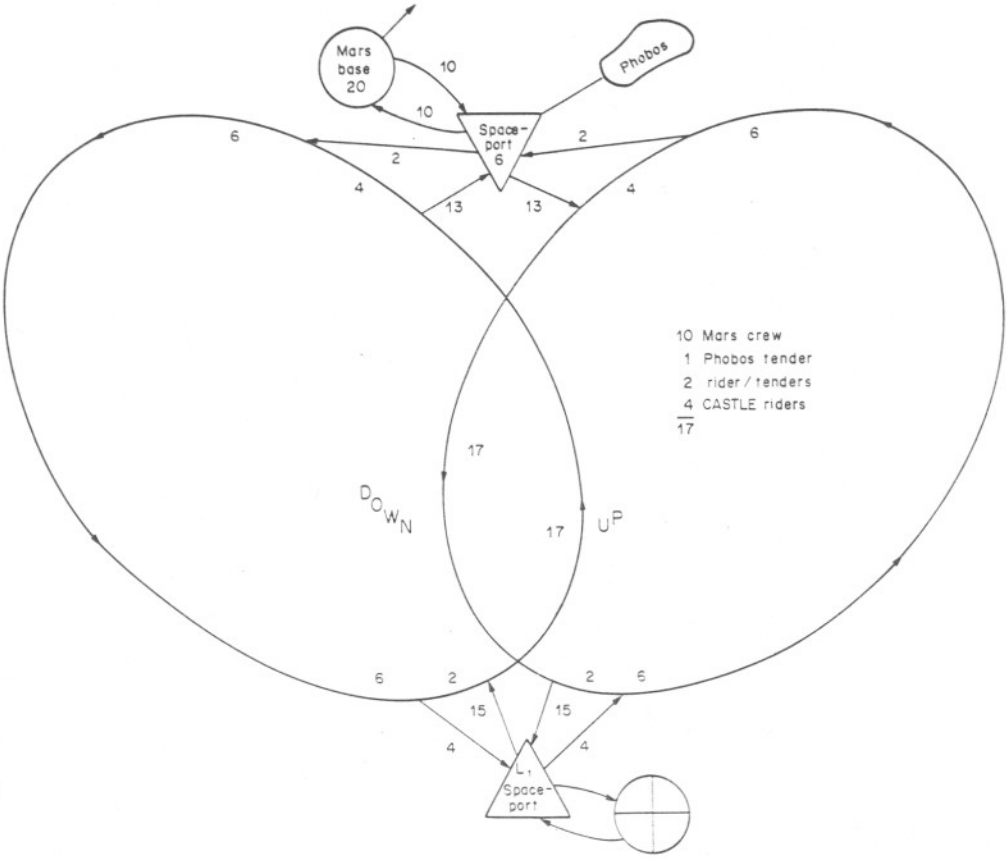

Fig. 13. Example crew loading schematic for Up/Down Escalator transportation mode.

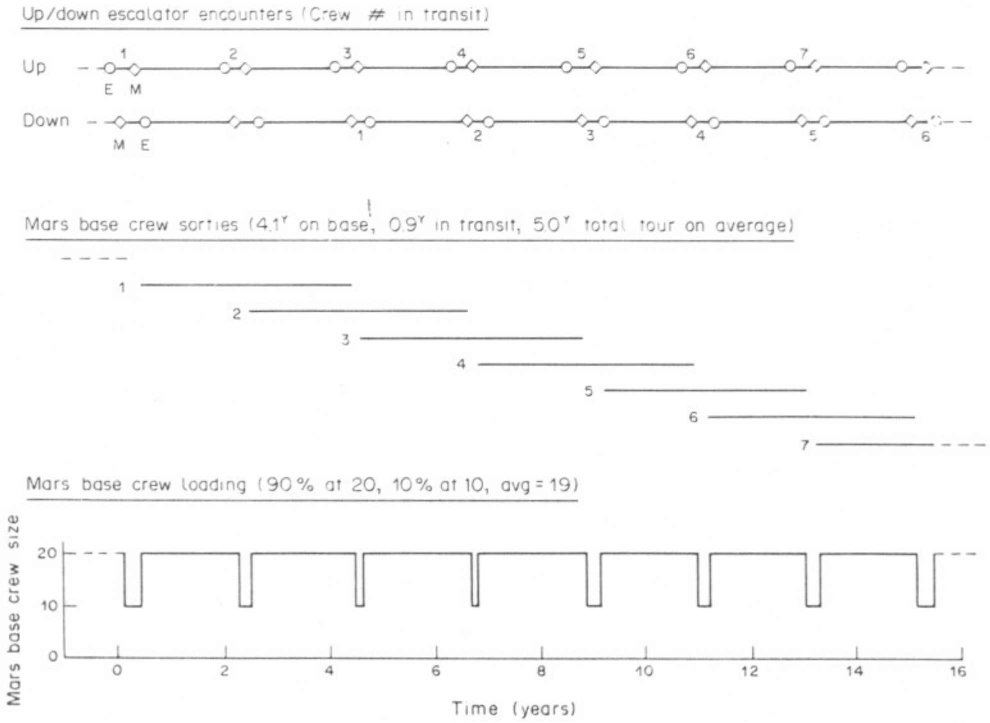

Fig. 14. Example crew flight schedule for Up/Down Escalator transportation model.

Table 5. Summary comparison of propellant and consumables over 15 years

	Conjunction	Visit	Up/Down Escalator	Down Escalator
LOX from Moon	22,519	17,006	21,975	16,216
LH_2 from LEO	3217	2430	3138	2317
LOX from Mars	919	656	919	459
LH_2 from Mars	131	94	131	66
LOX from Phobos	2992	1150	5834	4027
LH_2 from Phobos	427	164	833	575
CASTLE crew consumables	206	813	269	279
Total propellant	30,205	21,500	32,830	23,660

The propellant consumption and production rates for the four options discussed to this point are summarized in Tables 5 and 6.

4.4. *Phobos propellants emphasis*

Finally, the impact was evaluated of the exclusive use of Phobos propellants at Earth for the Down Escalator mode. In this mode, Phobos propellants are transported to Earth by NEP tankers. Two options were considered, namely, exclusive use of Earth propellants for the NEP vehicle and the use of Phobos or Mars resources for NEP Vehicle. The MPD thrusters can run on several different propellants with similar performance. These include many that may exist at Phobos or could be made there: methane, CH_4; ammonia, NH_3; N_2; liquid sodium, Na or even liquid aluminum, Al. It would be necessary to use the same NEP propellant for both legs of the journey in order to maintain the same propulsion system. Table 7 summarizes the performance of this option. It can be seen that the total propellant required is now 8576–8921 mt, depending upon NEP propellant source, as opposed to the previous Down Escalator case of 23,660 mt: about a 60% reduction in total propellant need.

Table 6. Extraterrestrial propellant production rate (average in kg/day)

	Conjunction	Visit	Up/Down Escalator	Down Escalator
Moon LOX	4113	3106	4014	2960
Mars LOX	168	120	168	84
LH_2	24	17	24	12
Phobos LOX	546	210	1066	735
LH_2	78	30	152	105

5. SUMMARY

In the beginning it had been thought that the circulating orbit modes would use significantly less propellant than the conjunction mode because the circulating orbit modes do not require the repeated injection of CASTLEs to and from Mars. Because all the circulating orbit modes have higher planet-relative velocities than the minimum-energy conjunction orbits have high delta-Vs are required for Taxi vehicles executing hyperbolic rendezvous maneuvers. These high delta-Vs combined with the requirement for Taxis to transport CASTLE refurbishment mass and propellants for CASTLE propulsive maneuvers

Table 7. Down Escalator mode with Phobos-supplied propellants

● Cryogenic propellant requirements	Metric tons over 15 years	Average production rate (kg/day)
LOX from Moon	0	0
LH_2 from LEO	0	0
LOX from Mars	459	84
LH_2 from Mars	66	12
LOX from Phobos	6030	1100
LH_2 from Phobos	861	157
Total LOX/LH_2 propellant	7416	
Amount returned to earth using NEP freighters	2289 (7 sorties at 327 mt each)	
● NEP requirements (15 years)	All NEP propellant supplied by Earth	NEP return propellant supplied by Phobos
NEP propellant from Earth (mt)	1505	178
NEP propellant from Phobos (mt)	0	982
Total NEP propellant (mt)	1505	1160
● NEP sortie characteristics		
Input power P_e (MWe)	7	7
Specific impulse (s)	5000	5000
Overall efficiency	50%	50%
Mass at Earth departure (mt)	287	98
Mass at Phobos arrival (mt)	213	73
Mass at Phobos departure (mt)	540	540
Mass at earth return (mt)	399	399
LOX/LH_2 payload returned (mt)	327	327
NEP propellant expended (mt)	215	166

result in the circulating orbit modes requiring similar total propellants as the conjunction mode. Because the VISIT orbit mode has low planet relative velocities, which implies lowered Taxi delta-Vs, and because there are no large deterministic delta-Vs, the total propellant requirement is less than both the conjunction and Up/Down Escalator modes. The propellant required for a single Down Escalator is also lower due to a single CASTLE vehicle being used. Note however that is it not half of the Up/Down Escalator mode because the basic requirement is still to maintain 20 people on average on the Martian surface.

CASTLE crew and passenger consumables are also shown in Table 5. The relatively large amounts for the Down Escalator and VISIT modes are due to extended CASTLE stay times required by all Down Escalator crews on the trip to Mars and some VISIT Mars crews on very long flights to and from Mars (in some cases up to 3 years).

Performance sensitivity to variations in several parameters was studied for a single orbit of the Down Escalator (see Table 8). Some of these results can be extrapolated to changes in CASTLE refurbishment mass and to changes in consumable rates are probably applicable to all circulating cases. However, the large sensitivity of performance resulting in changes in the Taxi crew module mass comes from the large delta-Vs on the Up or Down Escalator required for rendezvous maneuvers near both Earth and Mars and therefore is probably not applicable to the VISIT orbit mode. The VISIT mode performance may show a larger sensitivity to consumable rate because of the long Mars crew flight times required.

Even with the reliance upon extraterrestrial resources, especially propellants, 2000 to 3500 metric tons of LH_2 and consumables must be lifted from the surface of the Earth to the LEO for a Mars transportation system. Assuming the existence of a future Heavy Lift Launch Vehicle (HLLV) capable of placing 200 metric tons in LEO, from 12 to 18 HLLVs must be launched to support a Mars base over a 15 year period.

It is a surprise to see the small propellant production requirement for Phobos relative to the Moon. In the case of the Up/Down Escalator, for every kilogram of material (propellant or consumable) required to be at L_1 for use and/or transport to Mars, more than 5 kg of LEO LH_2 and lunar LOX are required to transport this single kilogram to L_1. This high ratio is caused by the need to transport people, consumables and LH_2 propellants through the deep gravity well from LEO to L_1 and back as well as the need to transport lunar LOX to L_1 and to LEO. The cost of this is seen in Table 6 which summarizes extraterrestrial propellant production rates. It is clear that lunar LOX production is a major undertaking. There is tremendous expense in relying upon Earth-based propellants. For this reason, the more extensive use of Phobos propellants was examined.

As the data shown in Table 7 illustrates, extensive use of Phobos-derived propellants in near-Earth space significantly reduces the total propellants required to operate the Down Escalator transportation system. This result can be extrapolated in a similar fashion to all transportation modes studied. An added advantage of the use of Phobos propellants at Earth is the elimination of an extensive LOX propellant manufacturing infrastructure on the surface of the Moon.

Propellant mass, while an important component in transportation mode comparison, is not the only ingredient. Several other factors need to be understood before deciding upon an "optimum" transportation system. Table 9 is an attempt to characterize and compare several other features of the four transportation mode cases studied. Some of the more important issues can be discussed. The number of CASTLEs required impacts the buildup and operating cost. The more CASTLEs there are, the more it will cost to put in place a full system and the more it will cost to operate. Tours of duty are long; typically from 5 to 8 years over the four options studied. For any future Mars base these long tours will be necessary. There are differences, however, between options on the percentage of Mars base crew tour actually spent on the surface of Mars. All else being equal more time on the surface is better than cruising between Earth and Mars. Another efficiency

Table 8. Performance sensitivity results for Down Escalator sortie No. 2

Parameter variation	Propellant from Earth–Moon system (m tons)	Propellant from Mars–Phobos system (m tons)	Total mission propellant (m tons)
Reference case[a]	1702	532	2234
CASTLE refurbishment mass			
5 m tons	1564	532	2096 (−6.2%)
10 m tons	1576	532	2108 (−5.6%)
15 m tons	1622	532	2154 (−3.6%)
Taxi crew module mass			
5 m tons	1398	376	1774 (−20.6%)
15 m tons	1937	739	2676 (+19.8%)
Consumables rate (on CASTLE)			
1 kg/person/day	1553	459	2012 (−9.9%)
2 kg/person/day	1577	469	2046 (−8.4%)

[a] Refurbishment mass = 20 m tons; Crew module mass = 10 m tons; Consumables rate = 3 kg/person/day.

Table 9. Transportation mode comparison chart

	Conjunction	Visit	Up/Down Escalator	Down Escalator
Number of CASTLEs	2	3	2	1
Tour of duty, yr	4.8	5.7–7.9	5	6.5
Mars crew flightime, yr	1.6	1.2–6.3	0.9	2.1
Mars Staytime, yr	3.2	1.6–5.9	4.1	4.4
Mars Staytime, % of tour	67	20–83	82	67
Phobos tender crew tour of duty, yr	4.8	5.7–7.9	4.3–5.0	6.5
CASTLE rider crew tour of duty, yr	—	5.0	4.3	4.3
CASTLE crew capacity	17	21	17	17
Number of sorties per 15 yrs	7	8	14	7
Number of personnel to Mars vicinity and return in 15 years	119	147	133	105
Mars spaceport/CASTLE crew to Mars surface crew ratio	1:3.3	1:1.5	1:1.1	1:2.0
CASTLE utilization eff, % time used to transport Mars surface crew	39	62	21	100
Transport mode systems requirements	Large propulsion system	Pressurized Taxi hanger	Pressurized Taxi hanger	Pressurized Taxi hanger
Other mission uses of CASTLE	Venus asteroids	Remote observation	Remote observation	Remote observation

parameter is the ratio of Mars spaceport and CASTLE crew to the actual number of people placed upon the surface. For reference, a typical large cruise ship crew to passenger ratio is 1:2 whereas a large passenger airplane operates at a ratio more like 1:10, including ground personnel.

Another consideration is the manner is which the CASTLE propulsion system should be implemented. Table 10 compares the velocity change requirement for the CASTLE in each of the four options investigated. The delta-V required in the conjunction case was split between the CASTLE and OTVs based at Earth and Mars. In the Escalator and VISIT cases all CASTLE velocity changes were executed by the Taxis in residence using propellant delivered by the Taxis at the hyperbolic rendezvous. Table 10 indicates that the conjunction mission is characterized by large delta-Vs and a high frequency while the VISIT orbits do not exhibit these properties. In terms of reliability and propulsion system capability this would argue for the use of VISIT orbits.

By no means is the work described here complete. Much more needs to be done in trajectory analysis and in performance modeling. In particular, buildup requirements and costs should be incorporated into transportation mode comparisons. Costs should include both development (non-recurring) and operations (recurring) elements. Buildup requirements need to be parameterized in order to see the effects of different schedule and resource availabilities for each option.

As stated earlier, the choice of Earth–Moon L_1 as a transportation node was not the result of a detailed comparison study of the various alternatives including other libration points, LEO, GEO, lunar orbit, high elliptical orbit and so-called Earth–Moon cyclers[14]. Before these comparisons can be made, extensive trajectory analysis is required especially to understand the phasing problem between a transportation node and a circulating CASTLE. To underscore this point, it should be noted that short Taxi flight time and minimum energy trajectories (<7 days) from Earth–Moon to circulating CASTLEs have yet to be found for arbitrary CASTLE flyby time. Unless the Moon, and thus, L_1, is in just the right position, long phasing orbits or high delta-Vs are required before a Taxi can be injected toward the hyperbolic rendezvous with the CASTLE.

In the area of technology variables, the use and effect of tethers on a Mars transportation needs to be studied. Tethers operating at both transportation nodes could reduce total delta-V by as much as 2 km/s; a significant reduction in injection energy requirements. The effect of such an emerging technology upon a Mars transportation system should be addressed.

Table 10. CASTLE velocity change requirements, m/s

	Conjunction	VISIT	Up/Down Escalator	Down Escalator
M/s per 15 years	36345[b]	1000	5159[c]	2734
M/s per CASTLE per 15 years	18172	333	2580	2734
M/s per CASTLE per sortie (avg)	4543	125	369	391
Number of major ΔVs per CASTLE	16	0	3	3
M/s per major ΔV (avg)	1298	0	627	627
M/s per major ΔV (min)	1011	0	270	270
M/s per major ΔV (max)	1646	0	1105	1105

[a] Assumes 50 m/s midcourse ΔV between planets.

[b] Assumes ΔVs split between Earth and Mars based OTVs and CASTLE. OTV total is 17592 m/s.

[c] Taxi propulsion system provides CASTLE ΔVs.

6. CONCLUSIONS

From this preliminary look at potential elements of a Mars transportation system, a few cursory conclusions can be drawn. The Conjunction mode provides regular access to the surface of Mars and for the fewest number of support personnel. In addition, CASTLEs designed for conjunction missions, can travel to and from other interesting solar system bodies; in particular, asteroids. The VISIT mode requires the minimum delta-V of all the modes; however, 3 CASTLEs are required to attain an acceptable sortie frequency and some crews are required to have tours of duty as long as 8 years, which is very undesirable. The Up/Down Escalator mode, like the Conjunction mode, provides regular access to Mars and maximizes crew staytime at Mars for reasonable tours of duty. This latter advantage is offset by the requirement for two CASTLEs and attendant increase in support crew personnel. The Down Escalator mode eliminates a CASTLE and reduces propellant requirements for a subsequent increase in crew flight time. This mode is also second only to the Conjunction mode in the efficient use of support personnel. Finally, the extensive use of Phobos resources in near Earth space, eliminating the use of Earth LH_2 and lunar LOX, significantly reduces overall propellant requirements of such a Mars transportation system.

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