Practical Methods for Near-Term Piloted Mars Missions

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Abstract

This paper investigates means for achieving human expeditions to Mars utilizing existing or near-term technology. Both mission plans described here, Mars Direct and Semi-Direct are accomplished with tandem direct launches of payloads to Mars using the upper stages of the heavy lift booster used to lift the payloads to orbit. No on-orbit assembly of large interplanetary spacecraft is required. In situ-propellant production of CH_4/O_2 and H_2O on the Martian surface is used to reduce return propellant and surface consumable requirements, and thus total mission mass and cost. Chemical combustion powered ground vehicles are employed to afford the surface mission with the high degree of mobility required for an effective exploration program. Data is presented showing why medium-energy conjunction class trajectories are optimal for piloted missions, and mission analysis is given showing what technologies are optimal for each of the missions primary maneuvers. The optimal crew size and composition for initial piloted Mars missions is presented, along with a proposed surface systems payload manifest. The back-up plans and abort philosophy of the mission plans are described. An end to end point design for the Semi-Direct mission using either the Russian Energia B or a U.S. Saturn VII launch vehicle is presented and options for further evolution of the point design are discussed. It is concluded that both the Mars Direct and Semi-Direct plans offer viable options for robust piloted Mars missions employing near-term technology.

Introduction: Getting to Mars with a Lunar Class Transportation System

Conventional plans for manned Mars missions involve multiple launches of HLVs to support the assembly on-orbit of spacecraft with dimensions greater than the space station, and masses on the order of 700 tonnes. The majority of such craft will be composed of cryogenic propellants, which will continually boil off over the course of the year or so required for vehicle assembly. The technology challenges and astronomical costs associated with the launch, assembly, fueling, on-orbit operations and quality control of such missions has caused many to relegate the first manned Mars mission to some future generation which, perhaps, may live in a universe where such things are possible. The conclusion resulting from this paradigm has been fatal to the Space Exploration Initiative (SEI) , as it has resulted in SEI being viewed as either a long-term unlimited expense Moon-Mars boondogle, or alternatively as an uninteresting Moon-only Apollo replay embodying no serious intent of carrying human explorers to the Red Planet.

On the other hand, if a means could be found by which the same class of transportation system needed for Lunar missions could be used to enable manned missions to Mars, the entire SEI would become practical, and not only a from technological standpoint, but also from a political and economic standpoint as well. Viewed another way, if a Lunar program is underway, the question of whether or not a Mars mission is possible will be posed in the form; "Can we do it with what we have now?" If this question can be answered in the affirmative, then humans may yet walk on Mars during the working lifetime of the present generation of engineers.

The real challenge facing Mars mission designers, then, is to solve this problem: reduce the mass of the manned Mars mission to the point where an Apollo class transportation system can handle it. In 1990 a mission plan, known as "Mars Direct"[1,2,3] was devised at Martin Marietta which uses the leverage offered by the use of propellants manufactured on the Martian surface to do exactly that. Subsequently a collaborative discussion between the present authors and Mike Duke of the NASA JSC Exploration Programs Office produced an alternative "Semi Direct"[4] architecture which also meets this objective while eliminating some of the weaknesses and constraints present in the original Mars Direct plan. A version of this Semi Direct option has since become the basis for a Design Reference Mission Study conducted in collaboration by personnel from NASA's JSC, Marshall, Ames, and Lewis Research

Centers[5]. A third option, which we call the Hybrid-Direct because it is intermediate in characteristics between the Direct and Semi-Direct plans is also possible.

Mars Direct, Semi-Direct, and Hybrid-Direct

The Mars Direct plan works as follows: At an early mission opportunity, for example, 2001, a single heavy lift launch vehicle (HLV, Saturn V class or better) with a substantial upper stage lifts off the Cape and hurls onto direct trans-Mars injection (TMI) an unmanned payload. This payload consists of an unfueled methane/oxygen driven two-stage ascent an Earth Return Vehicle (ERV), several tonnes of liquid hydrogen cargo, a 50 kWe nuclear reactor mounted in the back of a methane/oxygen driven light truck, a small set of compressors and automated chemical processing unit, and a few small scientific rovers. This payload aerobrakes into orbit around Mars and then lands with the help of a parachute. As soon as it is landed, the truck is telerobotically driven a few hundred meters away from the lander, and the reactor is deployed to provide power to the compressors and chemical processing unit. The hydrogen brought from Earth is quickly catalytically reacted with Martian CO_2 to produce methane and water, thus there is no need for long term storage of cryogenic hydrogen on the Martian surface. The methane is liquefied and stored, and the water electrolyzed to produce oxygen, which is stored, and hydrogen, which is recycled through the methanator. Ultimately these two reaction (methanation and water electrolysis) combined with an auxiliary CO_2 reduction unit produce an amount of methane/oxygen bipropellant equal to 18 times the mass of the hydrogen imported from Earth. More than 90% of the bipropellant will be used to fuel the ERV, but 12 tonnes extra is produced to support the use of high powered chemically fueled long range ground vehicles.

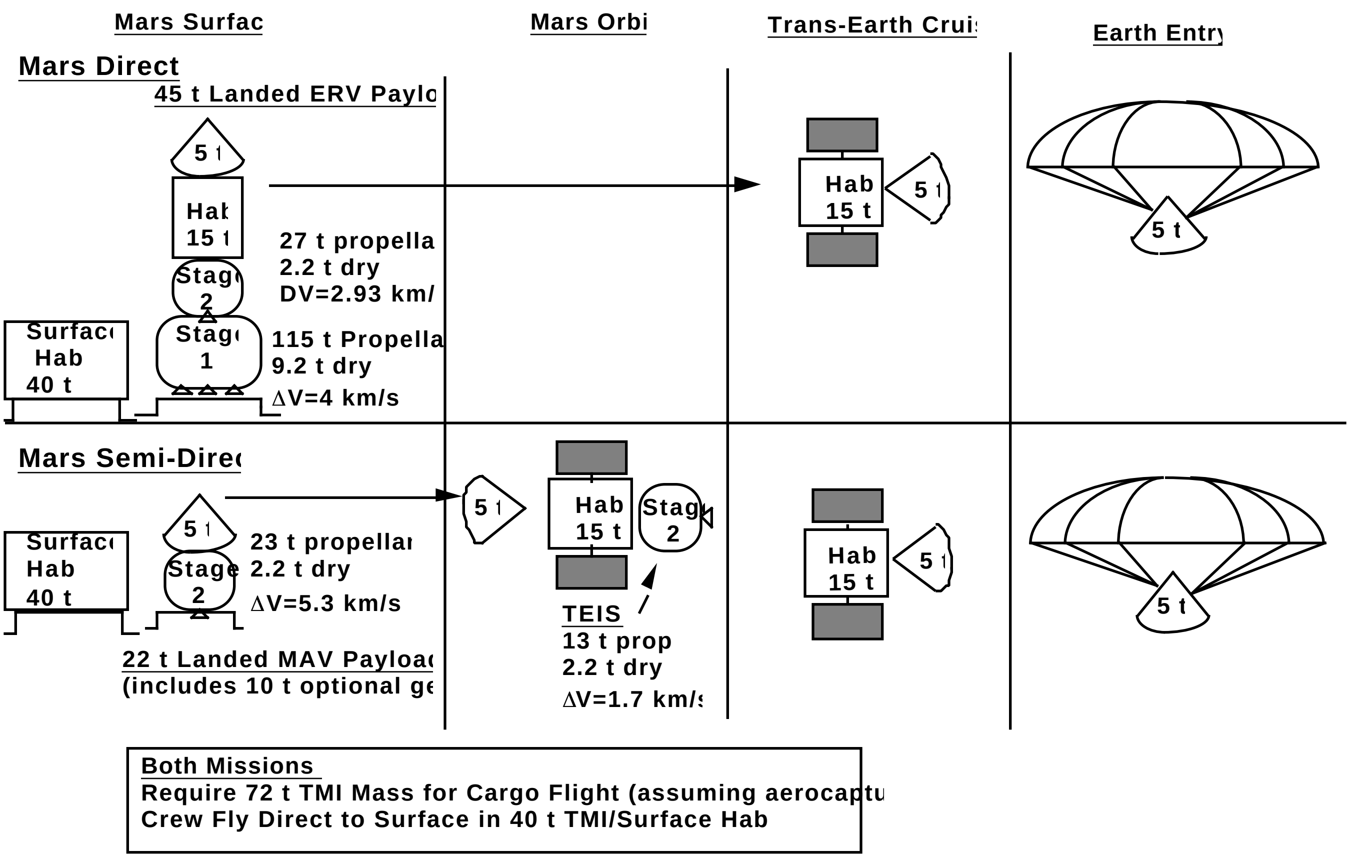

Fig. 1 Comparison of Mars Direct and Semi-Direct plans, assuming 72 t TMI capability for cargo and 60 t for crew. A 3 launch version (ERV, MAV, and Hab) of the Semi-Direct mission using less TMI capability or providing greater mass margin is also possible

The propellant production having been successfully completed, in 2003 two more HLVs lift off the Cape and throw their payloads onto trans-Mars injection. One of the payloads is an unmanned fuel-factory/ERV just like the one launched in 2001, the other is a habitation module containing a crew of 4, provisions for 3 years, a pressurized methane/oxygen driven ground rover, and an aerobrake/landing engine assembly. Artificial gravity can be provided to the crew on the way out to Mars by tethering off the burnt out HLV upper stage and spinning up at 1 rpm. The manned craft lands at the 2001 landing site where a fully fueled ERV and fully characterized and beaconed landing site await it. Assuming the surface rendezvous is accomplished as planned and the ERV checks out, the second ERV can be landed either at the same site or several hundred miles away to start making propellant for the 2005 mission. Thus every other year 2 HLVs are launched, for an average launch rate of 1 HLV per year to pursue a continuing program of Mars exploration.

An extensive description of the original baseline Mars Direct vehicle elements is given in reference 2.

The crew stays on the surface for 1.5 years, taking advantage of the mobility afforded by the high powered chemically driven ground vehicles to accomplish a great deal of surface exploration. With 12 tonnes of methane/oxygen bipropellant allocated for surface operations, about 24,000 ground kilometers can be traversed, ranging up to 500 km out from the base. Thus each mission can explore an area of approximately 800,000 square kilometers, which is roughly the size of the state of Texas. At the conclusion of their stay, the crew returns to Earth in a direct flight from the Martian surface in an ERV. All personnel sent to Mars thus spend all of the stay time at Mars on the surface where they can be shielded from cosmic radiation and have natural gravity. No one is ever left in orbit. Each hab flown out to Mars adds incrementally to the surface infrastructure. As the series of missions progresses, either a single major base or a string of small bases is built up on the Martian surface.

The Semi-Direct plan differs from the Direct plan described above in that the first launch, instead of delivering an unfueled ERV to the Martian surface, delivers an unfueled Mars Ascent Vehicle (MAV) and some cargo to the surface along with a fueled Earth Return Vehicle which is placed in a highly elliptical Mars orbit. The MAV then makes its own 24 tonnes of methane/oxygen propellant along with another 12 tonnes for surface vehicle use in the same manner proposed for Mars Direct. As in the Direct plan, the second launch then delivers the crew in their outbound hab to rendezvous with the MAV on the Martian surface, where they conduct 1.5 years of surface exploration and then ascend in the MAV to rendezvous in Mars orbit with the ERV. The ERV propulsion stage then performs Trans Earth Injection, and the MAV capsule is used as an Apollo-type Earth Crew Capture Vehicle (ECCV).

Compared to the Direct plan, the Semi-Direct plan has the disadvantage that the ERV hab is not available to the crew during the 1.5 year surface stay, and that a mission critical Mars Orbit Rendezvous is required on the return leg of the mission. On the other hand, the Semi-Direct plan only requires about 1/3 the propellant manufacturing needed by Mars Direct, thus reducing surface power requirements for propellant production to the 15 kWe level, which is about what is needed for base life support in any case. Furthermore, the ERV hab can be made much larger in the Semi-Direct plan than in the Direct, either affording the crew better accommodations on the return leg or allowing a larger crew. If TMI throw capability is limited, the Semi-Direct plan lends itself naturally to a 3-launch scenario, in which the MAV, ERV, and surface hab are each flown out on their own launch. Finally, while in neither the Mars Direct or Semi-Direct plan is the crew endangered if in-situ production of the return propellant (ISPP) fails, in the Direct plan continued ISPP failure can only be resolved by redesigning the mission, but in the Semi-Direct option the program could be retrieved by resorting to delivering a wet MAV to the Martian surface on a dedicated cargo flight.

A comparison of the Earth Return systems for the Mars Direct and Semi-Direct plans assuming a HLV/upper stage combination capable of delivering 72 tonne cargo flights and 60 t piloted flights to TMI is shown in Fig.1. An iconographic depiction of the Semi-Direct mission sequence is given in Fig. 2.

Finally, as a third alternative there is the Hybrid-Direct plan, which resembles the Semi-Direct option except that in this case the ERV cab only is delivered to Mars orbit, with TEI propulsion being provided by a in-situ fueled methane/oxygen stage lifted to Mars orbit with the MAV. This option is more mass-effective than either the Direct or Semi-Direct plans, but combines the operational disadvantages of both; to wit that a mission critical MOR is required, the ERV

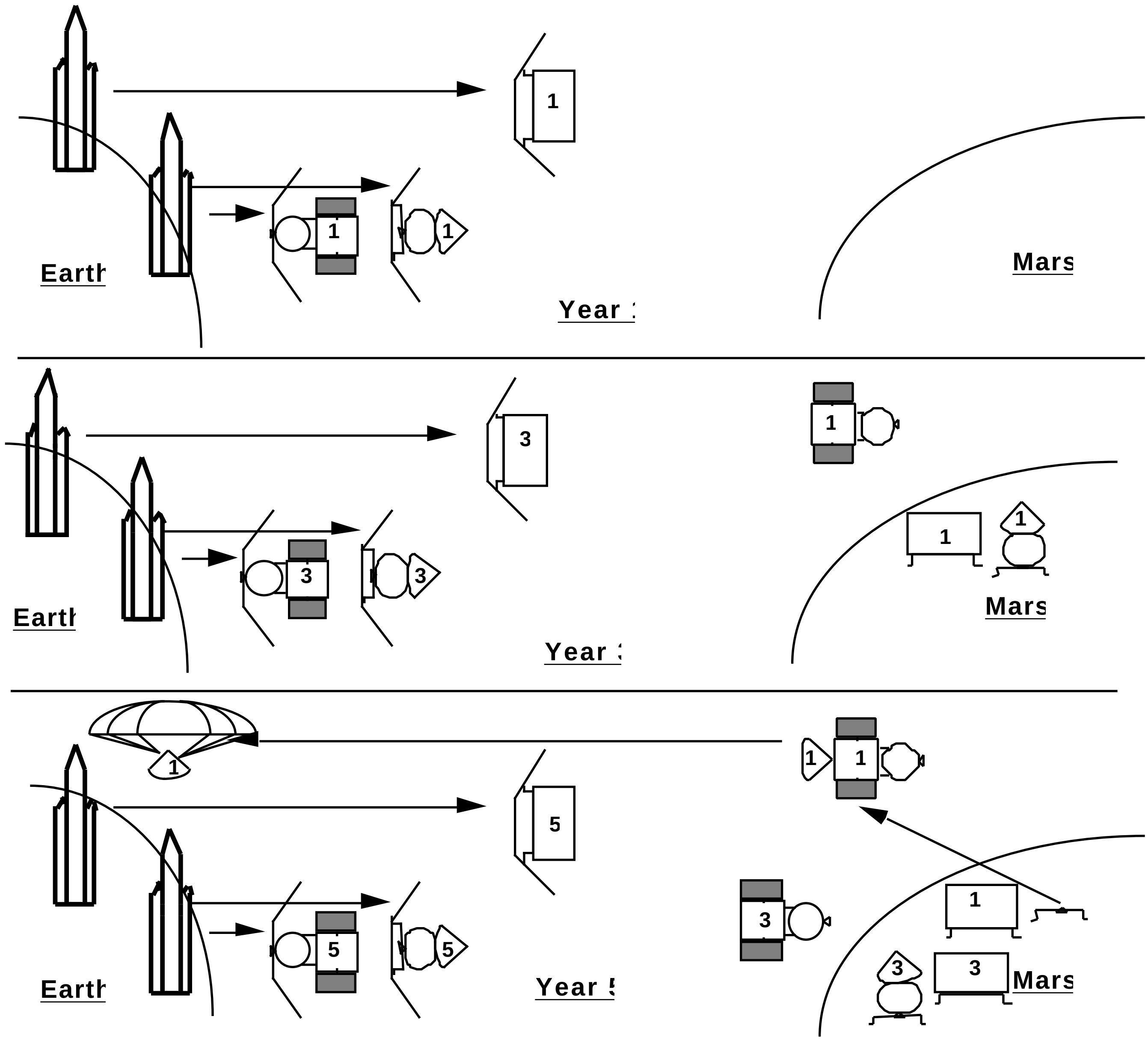

Fig. 2 An iconographic depiction of the Mars Semi-Direct mission sequence. Every two years two HLV's are launched, one to deliver a crew in the Transfer and Surface Hab (TASH), the other to deliver an umanned payload consisting of a self-fueling MAV And a ERV. Each mission adds another hab to the Martian surface, leading incrementally to a large base or a network of outposts. The Year 1 TASH is flown to Mars without crew. This creates a reserve hab for the first piloted flight, which arrives at Mars in the Year 3 TASH.

hab is not available to the surface crew, and a system redesign is required if ISPP should fail as a technology. For these reasons we believe that the Direct and Semi-Direct plans are the primary options to be considered. Because the Mars Direct plan has been discussed extensively is previous publications, in this paper we shall focus our attention mainly on an examination of the Semi-Direct option.

Choice of Trajectories

Much has been written in the past[6] about the necessity of achieving "quick trips" to Mars to reduce crew exposure to zero gravity and cosmic radiation. Two such options have been proposed to achieving quick trips: opposition class missions and accelerated fast transfer conjunction missions.

In the opposition missions, large amounts of propellant are expended to achieve high energy trajectories which allow the crew to perform round trip missions to Mars in about 1.5 years. However the trajectories employed are such that over 90% of the mission time is spend in interplanetary space and only 30 days or so are spent in the vicinity of Mars. The net result is a very high cost mission (because of large propellant mass and resulting on-orbit assembly requirements) with very low payoff (because the time available for exploration on Mars is minimized.) In fact, if the weather on Mars is unfavorable at the time of arrival, it is quite possible that an opposition class mission would be forced to leave Mars without achieving a landing. Furthermore, it has been shown[3,7] that, despite their comparatively short total duration, opposition missions actually subject the crew to greater cosmic ray doses and zero gravity exposure than minimum energy conjunction missions. This is a result of fact that virtually all of the opposition mission time is spent in interplanetary space, whereas at least half of a conjunction mission's time is spent on the surface where natural gravity and substantial radiation protection (radiation doses received on the Martian surface, even without taking advantage of the use of Martian regolith as shielding, are about a quarter of those received in interplanetary space) is available. Thus the opposition mission has been found to offer maximum cost, maximum risk, and minimum return, and has been dropped from further consideration by most of the Mars mission planning community, the present authors included.

The other type of fast transfer, the accelerated conjunction, has a more substantial basis in reason. An absolute minimum energy conjunction mission would consist of a Hohmann transfer taking 0.7 years each way to Mars and back, with a 1.2 year surface stay. With very little extra propulsive ΔV, this flight plan can be altered to consist of two 0.5 year transfers plus a 1.5 year surface stay. This would be beneficial, as the surface stay fraction of the mission is increased from 46% to 60%, with the total round trip time reduced slightly. If more propulsive ΔV is added, this process can be taken even further, but at a significant cost to the mission in terms of reduced delivered payload. Such payload reductions do not merely reduce mission capability, they are a source of risk to the crew, as they imply the thinning out of redundancy of backups to various mission-critical propulsion, control, and life-support systems. The failure of any one of these systems would represent a much more deadly threat to the crew than the roughly 1% statistical incidence of cancer caused by a year of exposure to interplanetary levels of cosmic radiation. Thus if crew safety is the objective, attempts to accelerate conjunction trajectories beyond certain limits must be seen to be misconceived.

In Fig. 3 we have shown the average transit times to Mars for opportunities between the years 2003 and 2011 as a function of the C3 (C3 is the square of the velocity of departure from a planet) leaving Earth and the hyperbolic approach velocity of arrival at Mars. A minimum C3 of 15 is required simply to assure the capability of performing a transit to Mars during any opportunity. It can be seen that by increasing the C3 to 25, a substantial reduction (about 70 days) in transit time is achieved. This requires a ΔV leaving LEO only 0.42 km/s greater than that needed for a C3=15 transfer. However, if we push harder to a C3 of 40 (which requires 1.04 km/s greater ΔV than a C3=15 transfer) the further reductions achieved (about 10 days) are marginal. In other words, a C3 of 25 achieves the lion's share of the transit time reduction that is realistically possible, and beyond this we rapidly reach the point of diminishing returns, where large amounts of ΔV are required to produce very limited results. Furthermore, trajectories with energies about C3=25 have the interesting property that they can be made to return to the point of departure exactly 2 years after leaving, thus giving a piloted spacecraft the option of a "free return" to Earth if a decision is made to abort the mission. For these reasons we have baselined an outbound C3 of 25 km^2/s^2 as optimal for piloted missions. for unmanned cargo vehicles a C3 of 15 is used, as transit time is not an issue. If hyperbolic velocities of arrival at Mars are limited to 5 km/s to keep aerocapture technology requirements modest (V_{hyp}=5 km/s at Mars produces atmospheric entry

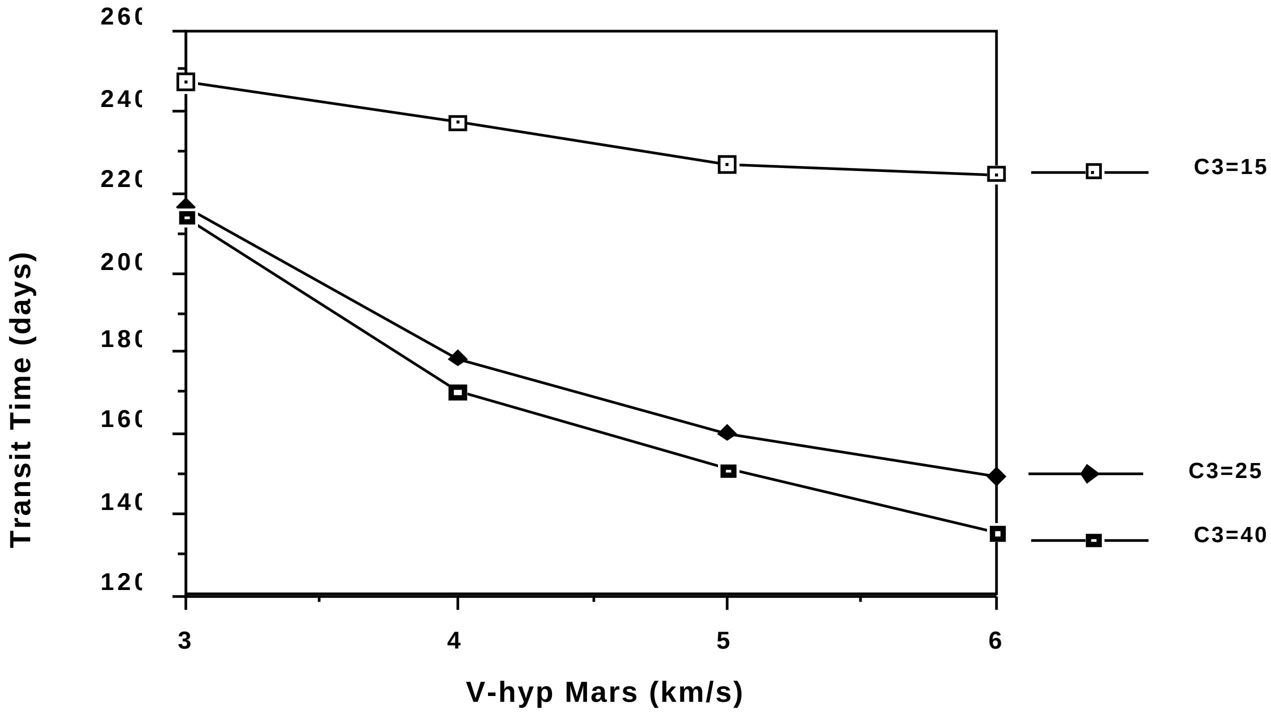

Fig. 3. Average trip time outbound to Mars for the years 2003-2011. It can be seen that the lion's share of transit shortening is achieved with C3=25 km^2/s^2.

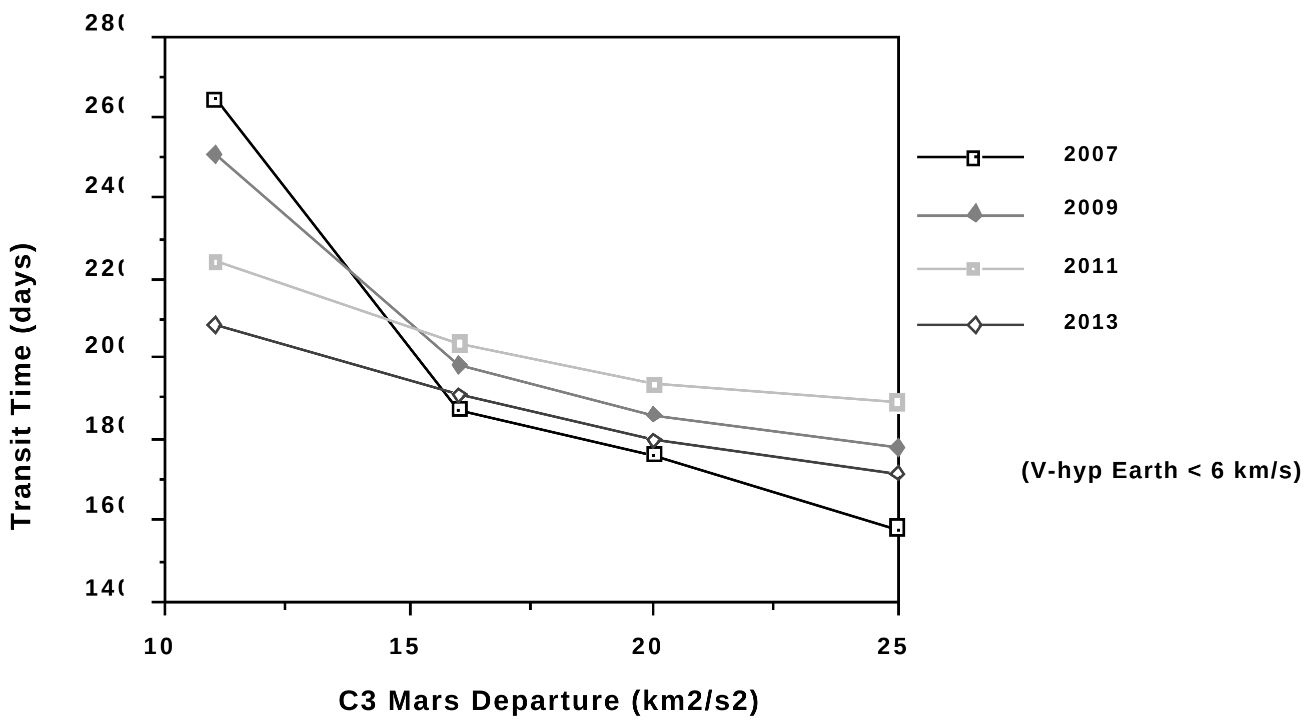

Fig. 4. Transit times from Mars to Earth 2007-2013. It can be seen that the lion's share of transit shortening is achieved with a TEI C3 of 16 km^2/s^2.

velocities of 7 km/s, less than the 8 km/s faced routinely by the Space Shuttle and much less than the 11 km/s encountered by Apollo capsules), then the average transit time outbound will be about 160 days. Since from an engineering point of view it is necessary to design propulsion stages and payloads for a fixed C3 and take whatever transit time the celestial mechanics of a given year allows, the actual outbound transits will vary from a minimum of 113 days for the 2003 opportunity to 190 days for the 2011 opportunity.

In Fig. 4 we show the Mars to Earth transit times for all return launch windows between 2007 and 2013. once again, it can be seen that a sharp reduction in transit time can be achieved by slightly increasing the departure C3 (to C3=16) above its minimum value (of C3=12), but that subsequent gains are marginal. for these reasons we have baselined a Mars departure C3 of 16 km^2/s^2. Earth arrival hyperbolic velocities are kept below 6 km/s (atmospheric entry velocities of 12.44 km/s) in order to keep aero entry requirements within reach of Apollo capsule technology.

If these trajectories are used, then the ΔV's required (including 5% gravity losses leaving Low Earth Orbit (LEO), 2 % leaving Mars, and 0.1 km/s mid-course corrections each way) are 4.15 km/s for cargo leaving LEO, 4.6 km/s for piloted vehicles leaving LEO, and 1.73 km/s departing a 250 km by 33000 km elliptical parking orbit (1 sol orbital period) at Mars.

Required HLV and Propulsion Technology

In Table 1 we show the amount of payload that can be delivered to the Martian surface from a single launch of an HLV that can lift 200 tonnes to a 300 km circular LEO orbit. This is the amount that could be lifted by either a Russian Energia-B or by a U.S. Saturn-V derived booster scaled up to incorporate 7 F-1 engines in the first stage instead of the original vehicle's 5 (a Saturn VII). We show variants for both the cargo and piloted outbound trajectory and for the assumption that the third stage of this vehicle is either a cryogenic H_2/O_2 chemical stage with an Isp of 460 seconds or a near-term nuclear thermal rocket (NTR) with an Isp of 870 seconds. (Such NTR performance represents 1960's NERVA technology. Current Russian NTR fuel elements could give Isp's of 960 s, or more, allowing a 8 t increase in TMI capability over the estimates given here.)

In Table 1 aerobrakes are assumed to have a mass equal to 15% of the object they are decelerating, NTR stages are assumed to consist of a 25 klb thrust engine (sufficient to throw a 200 t in LEO payload onto TMI with minimal gravity losses if 3 perigee burns are used), a 1.5 t shield, and a tank with a mass of 20% of the hydrogen it contains. Cryo stage dry mass fractions are taken at 15%, that of CH_4/O_2 and MMH/NTO is taken at 8%. Post aerocapture periapsis raise ΔV was taken as 0.1 km/s. Specific impulse for CH_4/O_2 is taken as 375 s, MMH/NTO as 320 s. Aerobraked options employed trajectories with hyperbolic approach velocities of 5 km/s, while those options employing propulsive capture used somewhat slower transfer orbits with hyperbolic approach velocities of 4 km/s in order to minimize the capture ΔV (to 1.6 km/s) The landing ΔV is taken as 500 m/s, accomplished by CH_4/O_2, with a lander drymass equal to 10% of the payload it is delivering. The payload delivered to Mars orbit (excluding aeroshell) in all cases is 1.28 times the payload delivered to the surface.

It can be seen that the use of NTR for TMI is highly advantageous, increasing the delivered payload by 77% for cargo and 100% for piloted flights. However, it can also be seen that NTR offers no significant advantage over chemical propulsion for Mars orbital capture. This is because the large dry mass of the NTR stage combined with the large amounts of hydrogen propellant boiloff during trans-Mars cruise (even a H_2/O_2 chemical stage is only 14% hydrogen, NTR propellant is 100% hydrogen) destroys any performance advantage resulting from the high specific impulse of NTR when applied to a modest ΔV. This logic holds even more forcefully for the trans-Earth injection burn, which occurs 2 years into the mission and is much more conveniently accomplished by a space storable CH_4/O_2 stage.

Table 1 Payload Delivery to Martian Surface from 200 tonne to LEO HLV

Mission	TMI Stage	TMI Throw	Payload Delivered to Surface (tonnes)				
				Mars Orbit Capture System			
			Aero	NTR	H_2/O_2	CH_4/O_2	MMH/NTO
Cargo	H_2/O_2	57.5	35.9	29.2	28.5	27.3	25.9
Piloted	H_2/O_2	46.7	28.9	21.0	20.5	19.2	17.2
Cargo	NTR	101.7	63.1	53.1	50.4	48.4	45.8
Piloted	NTR	94.2	58.4	43.2	41.4	38.6	34.8

Staging off the NTR stage immediately after TMI also reduces the total burn-time required of the NTR engines. This allows the NTR to either be run hotter than would otherwise be possible and therefore producing a higher Isp, or reducing the specifications, and thus development cost of the NTR program. For these reasons we recommend staging off the NTR immediately after TMI. (If desired, the exhausted NTR stage can be strung several hundred meters out on a tether during trans-Mars cruise to provide a counterweight to make artificial gravity to the crew, and then discarded shortly before Mars arrival.)

It is clear from Table 1. that aerocapture is the optimal mode of Mars orbital capture (MOC) for use in these missions because all (for Mars Direct) or nearly all (for the Semi-Direct plan) of the TMI payload is destined for the Martian surface, and so all or nearly all of it must carry an aeroshield in any case. MOC via aerocapture in these plans thus eliminates a significant propulsive ΔV essentially "for free." Aerocapture in the plans we propose also faces smaller technological hurdles than in many other applications, since the conjunction class trajectory employed produces moderate entry velocities, and thus modest mechanical and thermal loads. The aerobrakes we require are also much smaller than those required for the far more massive traditional style missions, and if either flexible fabric low L/D or rigid bullet-shaped high L/D configurations are employed, can easily be launched "all-up" without any need for on-orbit assembly. In addition, the guidance, navigation, and control requirements on Mars Direct and Semi Direct aerocapture are less than in those plans where a subsequent Mars orbit rendezvous is anticipated, since it does not really matter exactly what orbit the vehicle captures into, (since the orbit will be "erased" after the vehicle lands, and even the ERV, which is left in orbit in the Semi-Direct mission only has to be accessed from the surface) so long as its inclination and argument of periapsis are within the broad tolerances that will allow access to the designated landing site. It may also be remarked that direct entry landings on Mars, which also would work well for Mars Direct and Semi-Direct, will be demonstrated by the MESUR mission currently scheduled for the late 1990's.

A Baseline Design for Mars Semi-Direct

A baseline system design for the Semi-Direct Mars mission could be conducted employing 2 launches of a 120 tonne to LEO HLV during each launch window to Mars (i.e. every other year. Such a launch vehicle can be readily assembled using space shuttle components[2] consisting of an ET core, four SSME's, two solid strap ons, and a H_2/O_2 second stage) An third stage with two 15 klb thrust NTR engines (NTRs of this size would be comparatively easy to develop and have wide application for unmanned planetary and GEO missions[8]) performs 2 perigee burns to throw the payloads onto trans-Mars injection. (Use of a single NTR engine with 3 perigee burns might also be acceptable here because only for a short time during the post-escape portion of the third burn would engine failure cause the crew to be stranded; if the engine fails prior to escape the aeroshield can be used to decay the spacecraft's orbit back to LEO.) After trans-Mars cruise aerocapture is used to insert the payloads into a highly elliptical Mars parking orbit (If a 200 t to LEO launch vehicle such as Energia B is available, essentially the same payloads can be delivered with an H_2/O_2 chemical third stage.) Using such systems, the following payloads can be sent to Mars.

Launch A; Cargo	Total MOC Payload 58 t
Earth Return Hab	15 t (to Mars parking orbit)
CH_4/O_2 TEI Stage	15 t (to Mars parking orbit)
Aeroshell	7.6 t (Expended during landing)
Lander (wet)	6.5 t (offloaded piloted lander)
MAV Capsule	4.0 t
Dry Ascent Stage	2.0 t (Common with TEIS)
LH_2	4.0 t (=36 t CH_4/O_2 & 18 t H_2O)
(2) 6 kWe DIPS	1.5 t
Chem plant	0.5 t
Cargo	1.9 t
Launch B; Piloted	Total MOC Payload 53.8 t
Aeroshell	7.6 t (Common with Cargo)
Lander (wet)	9.7 t (3.6 t dry + 6.1 t prop)
Surface Hab	30.0 t
Field Science Equip	2.0 t
(2) 6 kWe DIPS	1.5 t
Pressurized Rover	2.0 t
(2) Open Rovers	1.0 t

During the first launch opportunity, say 2001, both the Cargo "A" launch and the usually Piloted "B" launch are flown to Mars unmanned and their surface payloads landed at a common site. The MAV payload

Fig. 5 Mars Semi -Direct surface base. The large spherical transfer and surface hab provides very large crew accommodation at very low mass. The hab and the self-fueling CH_4/O_2 propelled MAV use common landing systems and each has its own 12 kWe DIPS power system. Since the first hab flies out unmanned, the crew of the first mission has available to them at the base two complete habs, two MAVs, 2 pressurized rovers, and 48 kWe of power. The CH_4/O_2 making unit is in the MAV lander, which remains on Mars after MAV ascent.
(Drawing by Carter Emmart)

thus delivered would then proceed to convert its 4 tonne supply of hydrogen feedstock into 36 tonnes of CH_4/O_2 (it only needs 24 tonnes for ascent; 12 tonnes extra are available for use by surface vehicles) and 18 tonnes of water. Then at the next opportunity, 2003, (and all subsequent) the Cargo "A" launch would be flown out unmanned but the piloted "B" launch would be deliver a crew of 4 to the Martian surface where they would rendezvous with the previously delivered payloads The crew of the first mission thus will have access to 60 tonnes of habitation, and in fact, if we discount the mass of the MAV ascent stages and their propellant, a total of 149 tonnes of useful mass will be available to the crew of the first mission while they are on the Martian surface. This is 5 times the useful surface payload carried by the baseline mission in NASA's 90 Day report[9] (which had twice our baseline Semi-Direct mission's initial mass in LEO). Each subsequent mission will deliver an additional hab, more rovers and science gear, another chemical plant and 24 kWe of power, and add 12 t of CH_4/O_2 and 18 t of water to the surface stockpiles. Thus with only 2 launches of a 120 t to LEO HLV per opportunity, an extremely muscular surface exploration capability is put in place starting on the very first mission, which capability will grow rapidly as the mission sequence proceeds. Furthermore, so long as the landing sites are chosen to be within one-way driving range by a CH_4/O_2 pressurized rover (up to 1000 km if the terrain is favorable), each crew will always have available to them while on the surface 2 completely redundant MAVs, 2 redundant ERVs in Mars orbit, and at least 2 complete surface hab modules either of which can house the entire crew for the duration. The plan may thus be considered very robust.

Fig. 6 Mars Semi-Direct transfer and surface hab main structure (aluminum spherical pressure shell and decks) has a mass of less than 1 tonne (with a strength 5 times that needed to react the hoop stress caused by its 5 psi atmosphere) and yet provides 200 cubic meters of useful living space to a crew of 4. The 2 m diameter airlock functions as solar flare storm shelter, with shielding provided by the consumables which are stored around it. The two 6 kWe DIPS units are located in the area below the lower deck surrounding the storm shelter. The hab lands with the pressurized rover strapped below it. The rover is subsequently lowered softly to the ground. (Drawing by Carter Emmart)

Fig. 7 Mars Semi -Direct Earth Return Vehicle (ERV) docked to the Mars Ascent Vehicle (MAV) capsule. The MAV capsule also functions as an Apollo-like Earth crew capture vehicle. The ERV main structure is identical to that of the surface hab, but its contents are offloaded to produce a lightweight vehicle. The CH_4/O_2 Trans Earth Injection stage is identical to the MAV ascent stage, but is sent to Mars only 60% full. (Drawing by Carter Emmart)

Optimal Crew Size and Composition

Much has been written about the desirability from a human factors point of view of having a large crew on a long duration Mars mission. However as the size of the crew drives the mass of all habitats, transportation stages and launch vehicles, it is essential from the point of view of cost and technical feasibility to keep the size of the crew to the absolute minimum. Furthermore, no matter how many back up plans and abort options are included in the mission design, it must be understood that in sending a crew to Mars we are definitely sending a group of humans into harm's way, and thus from a moral point of view the fewer people we have on board the initial missions, the better. Finally, no matter how desirable a large social group may appear to be for company on a long trip, any examination of the history of human exploration on Earth will show that it is entirely possible for long duration expeditions to be carried out successfully by *one person*, two people, or any other number.

The question then, is how many people are really needed on a piloted Mars mission. If the mission were to fail, far and away the most likely cause would be failure of one or more of the mission critical mechanical and electrical (propulsion, control, life support) systems employed. *The most important member of the crew then, the one on whom all other depend for their lives, is the mechanic.* Call this person a flight engineer if you wish, (he or she is an engineer in the sense of an old-time railroad locomotive or steamship engineer) but what is needed is an ace mechanic who can sniff out problems before they occur and fix anything that can be fixed. This job is so critical that, despite our preference for small crews, we recommend carrying two people capable of handling it.

The next most important job on the mission is that of *field scientist* The reason for this is simply that the purpose of the mission is to explore Mars, and so after those needed to get the crew to Mars and back, the next most important personnel are those essential to competently carrying out the exploration goals of the mission. Since no science return would also effectively be a form of mission failure, once again we recommend carrying two people that can do this job. One of the field scientists should be a geologist, oriented towards exploring the resources and understanding the geologic history of Mars. The other should be a biogeochemist, oriented towards exploring those aspects of Mars upon which hinge the question of past or present life. The biogeochemist would also conduct experiments to determine the chemical and biological toxicity of Martian substances to terrestrial plants and animals, and the suitability of local soils to support greenhouse agriculture.

And that's it. There is no need for people whose dedicated function is "mission commanders," "pilot," or "doctor." The mission will need someone who is in command, and a second in command for that matter, because in dangerous circumstances it is necessary to have someone who can make quick decisions for all without the need for electioneering or debate. But there is no room for someone whose sole function is to manage others to get the job done. Similarly there can be no one on board whose job description is "pilot." The spacecraft will be capable of fully automated landing, and piloting skills would at most be useful as a contingency backup to the automated flight system during a few minutes of the 2.5 year mission. If such a manual flight control backup is desired, then one or more members of the crew could be given cross training as a pilot (It is much easier to train a geologist to be a pilot than a pilot to be a geologist.) Finally, no ship's doctor as such. (It may be noted that the great Norwegian explorer Amundsen always refused to carry doctors on his expeditions, noting that they were injurious to morale and that the large majority of medical emergencies that occur on expeditions can be handled just as well by experienced explorers.) All members of the crew will be trained in first-aid, and expert systems on board and medical consultation from Earth will be available to diagnose readily treatable conditions (i.e. ear infections and the like). Such diagnoses could be assisted by having a member of the crew be someone who had either practiced general medicine at some point earlier in his or her career or who had been crossed trained to the level of knowledge of a medical assistant, and equip either with a country doctor's black bag. The biogeochemist would be a natural candidate for such a cross-trained role. However the idea of having a dedicated top-notch doctor on-board who spends his or her time on the mission reading medical texts and honing skills by practicing surgery with virtual reality gear, or worse, making a pest of himself by subjecting the rest of the crew to an in-depth ongoing medical study, is simply ludicrous.

To summarize in "Star Trek" terminology, what a piloted Mars mission needs are two "Scotty's" and two "Spock's". No "Kirk's," "Sulu's," or "McCoy's" are needed, and more importantly neither are the berths and rations to accommodate them.

Habitats and Consumables

In Table 2 we show the consumables required for each member of the crew per day and the totals required to support a crew of four in each of the two habitation systems (Mars Transfer and Surface Hab (TASH) and the Earth Return Vehicle (ERV)) hab for each leg of the mission. The numbers given under the Need/man-day column are NASA standards[10], except that we have replaced 0.13 kg/day of dehydrated food with 1.0 kg/day of whole (wet) food. Such a mixed diet is much better for crew morale on a long mission than dehydrated rations only, and actually costs the mission very little in the way of added mass, since the water content of the whole food serves to make up for the losses in the potable water recycling system

The large benefits accruing to a strategy of using in-situ resources can be seen between the lines in Table 2, as without the water and oxygen manufactured on the Martian surface by the MAV chemical plant, an additional 13 tonnes of consumables would have to be shipped out with the crew on the Mars Transfer and Surface Hab. This would increase the required consumables from 9 tonnes to 22 tonnes, which since we only have the capability of delivering a 36 tonne hab would be very difficult to accommodate. As noted above, each MAV produces 18 tonnes of water in advance on the surface, which will provide an excess over NASA nominal requirements in water availability which should be a real plus for the morale of a hardworking crew on a desert planet. It can also be seen that each Hab flies out to Mars with enough food for an 800 day mission which also allows it to suffice for a 2 year free-return abort. In the latter case the crew in the Hab will have to exploit the 6 tonnes of CH_4/O_2 propellant in the lander stage (unneeded as propellant in the event of a free return, which is concluded by aerocapture into Earth orbit), and reduce their use of wash water to 40% NASA nominal levels. This will be uncomfortable and bad for morale, but it could be endured and survived, which is the only issue in the event of such an abort.

Given these consumable requirements, the mass allocations for the ERV hab and the Transfer and Surface Hab can be assigned, and are presented in Table 3. Since the ERV travels back to Earth attached to the MAV capsule (which is used for earth entry), we list them together.

The subsystem mass allocations in Table 3 represent good targets that should be achievable using near-term technology and a disciplined engineering design. However should the required subsystem masses exceed these allocations, very large margin can be provided by shifting the mission to a 3-launch scenario, in which the TASH, the ERV, and the MAV are each sent out to Mars by a separate HLV launch. In that case, the ERV mass could be increased by 67%, to 25 tonnes instead of the current 15. the MAV surface payload could be increased even more, by 188%, allowing 39 tonnes to be landed instead of the current 13.5.

Table 2. Consumable Requirements for Mars Semi Direct Mission with Crew of 4

Item	Need/man-day	Fraction Recycled	Wasted/man-day	ERV Requirement	TASH Requirements		
				200 day Return	200 day Out	600 day Surf	Total
Oxygen	1.0 kg	0.8	0.2	160 kg	160 kg	0*	160 kg
Dry Food	0.5 kg	0.0	0.5	400	400	1200	1600
Whole Food	1.0 kg	0.0	1.0	800	800	2400	3200
Potable Water	4.0 kg	0.8	0.0**	0	0	0	0
Wash Water	26.0 kg	0.8	5.2	4160	4160	0*	4160
Total	32.5		6.9	5520	5520	3600	9120

* Oxygen and water are available on Mars surface from in-situ sources accessed by MAV before TASH launch. In event of 2-year free-return abort, oxygen and water (@ 40% nominal washing allocation) can be provided by using 6 t of CH_4/O_2 in lander stage

** Potable water lost due to inefficiency of recycle is made up by water added to system due to use of whole food.

Table 3. Mass Allocations for 2-Launch Mars Semi-Direct Mission Plan

Earth Return Vehicle Hab	
ERV Hab Structure	4.0 tonnes
Life Support System	2.5
Consumables	5.5
Electrical Power	1.5
Reaction Control Sys	0.5
Com & Info Managment	0.1
Spares and Margin	0.9
ERV Hab total	15.0
MAV Capsule	4.0
Crew	0.4
EVA Suits	0.4
Samples	0.2
MAV Total	5.0
Total ERV Hab/MAV	20.0 tonnes
Transfer and Surface Hab	
TASH Structure	7.0 tonnes
Furniture and Interior	2.0
Life Support System	4.0
Consumables	9.2
(2) 6 kWe DIPS	1.5
Reaction Control Sys	0.5
Com & Info Managment	0.2
Crew	0.4
EVA Suits	0.4
Lab Equipment	2.5
Field Science Equip	2.0
Pressurized Rover	2.0
(2) Open Rovers	1.0
Spares and Margin	3.8
TASH Total	36.5

Surface Systems Architecture

The surface systems architecture that we recommend is modular, flexible, robust, and takes maximum advantage of the use of local resources to leverage all aspects of the mission. On the very first mission, two transfer and surface Habs are available, either of which alone is fully capable of supporting the crew for the entire surface stay. Two complete Mars Ascent and Earth Return Vehicles are also available. A total surplus of water equal to 3 times the minimum requirement is available (produced by the two MAV's), as is a food cache sufficient to support the crew for four years (triple the planned surface stay). The crew has available for use 2 pressurized rovers and 4 open rovers, all of which run on CH_4/O_2 propellant. A total of 24 tonnes of this propellant is available on the surface to support these vehicles, sufficient to allow up to 48,000 km worth of travel by the pressurized rovers or triple that if the open rovers are employed instead. In addition to the rovers, 9 tonnes of scientific equipment are also available. The MAVs and pressurized rovers can be used as short duration safe-havens for the crew, and counting these plus the two large Transfer and Surface Habs, a total of 6 habitable volumes are available to the crew at the base. Since each MAV and TASH deliver a set of 4 spacesuits to Mars, 4 sets of spacesuits are available for the use of the crew.

Each MAV and TASH lander is equipped with its own set of two 6 kWe Dynamic Isotope Power systems (DIPS), either of which can produce the bare minimum power required for life support or in-situ propellant production. Each spacecraft is thus redundant in terms of its power production. However after the landing is accomplished, the four pairs of DIPS present on the surface can be linked together in a grid. Once this has been done, each DIPS will have not one, but 7 other units as backups. Total installed power at the base is 48 kWe, about 8 times the minimum required for survival. Much more power can be generated for limited periods of time (either at the base or at remote sites) by using the CH_4/O_2 engine on any one of the 6 vehicles to turn an electric power generator.

Using the same ISRU units responsible for propellant manufacture, unlimited quantities of oxygen can be readily produced on the Martian surface out of the CO_2 which comprises 95% of the Martian atmosphere. However nitrogen and argon combined only compose about 4.3% of the Martian atmosphere, and thus buffer gas will be much harder to come by. It is thus imperative that the habitats and pressurized vehicles operate at the lowest buffer gas partial pressures possible. The 5 psi (3.5 lbs O_2,1.5 lbs N_2) atmosphere used in Skylab is therefore recommended.

Apollo crews operated on 2-week missions in an atmosphere consisting of 5 psi oxygen and no buffer gas. Since the maximum rover excursion will be of this order, this is what we recommend for the pressurized rovers. Such a low-pressure rover would require no airlock. Instead the astronauts inside would simply don their spacesuits, valve off the pure oxygen atmosphere inside to Mars, and then open the hatch and walk outside. Assuming a rover interior volume of 10 cubic meters, 3.3 kg of oxygen would be lost each time the rover was depressurized in this way. If part of the rover's interior atmosphere were pumped into a compressed oxygen cylinder prior to valving, oxygen losses would be reduced further, but in any case the losses could easily be made up by in-situ production of oxygen at the base. The low-pressure rover would allow the use of a low pressure (3.8 psi oxygen, no buffer gas, as in Apollo) spacesuit for EVAs, with no pre-breathing required. Such a suit would be the lightest and most flexible possible, and thus enhance the quality of surface science performed. Since the oxygen is replaceable, a simple once-through system in which a used lung full of air is vented directly to the environment (in the manner of SCUBA gear) would be feasible, allowing a great simplification in space suit design. Such a simplification would not only further the goal of reduced spacesuit mass, but would dramatically enhance spacesuit serviceability, reusability, and reliability, making possible a Mars surface mission incorporating not tens, but *thousands* of EVAs.

Assuming a breathing rate of 5 gallons a minute, each astronaut using such a low-pressure oxygen "scubasuit" would expend 1.3 kg of oxygen in the course of a 4 hour EVA. Thus if 2 astronauts were to perform 2 EVAs each per rover excursion day, venting the rover twice in the process, 12 kg of oxygen would be used up. If the rover were to be operated in this manner every day of the 500 day surface stay, a total of 6 tonnes of oxygen would be used up. Wasting this much oxygen would be a burden if it had to be transported from Earth, but if produced on Mars would only require 200 days of operation of an ISRU plant driven by a single 6 kWe DIPS.

Backup Plans and Abort Philosophy

In the past, many Mars mission plans were constructed around trajectory abort options Such strategies greatly increased mission mass without increasing mission effectiveness because they required carrying sufficient propellant to Mars orbit to enable a high-energy opposition-class return trajectory to Earth. If such an abort was not exercised, all of the extra mass delivery entailed by such a strategy was for nought. Moreover, the opposition return trajectory subjects to crew to 1.5 years of continuous deep space radiation doses (probably in zero gravity as well), high solar radiation during a close in pass through the inner solar system, and very high g-loads at Earth return. All in all, such an abort return may be problematical to survive, and obviously, even if the crew does survive, the mission is a complete loss from the standpoint of Mars exploration. Rather than design the mission around such options, our strategy is based upon creating a safe haven in advance on the Mars surface, and aborting to it as our primary option. Such a haven can be reached much more quickly by an outbound crew than Earth can, and is thus much more likely to represent a real source of help in the event of trouble. Our primary abort option is thus the same as our primary mission mode, imposes no mass penalty, and its invocation still allows the mission to be carried out. Put another way, rather than design the mission around abort options, we have chosen to design it around a hierarchy of backup plans.

The abort/backup philosophy begins in LEO with the design of the TMI stage, which incorporates two 15 klb thrust NTR engines in order to provide the ability to complete the TMI burn in the event of the loss of one engine. This strategy offers large benefits, both for the cargo and the human missions. The TMI stage for the human missions pushes only the transfer and surface habitat (TASH) with its aeroshield and landing stage towards Mars; no Earth crew capture vehicle (ECCV) is incorporated into this flight. As the TASH is a payload destined for the Martian surface, an ECCV would only be useful for aborts back to Earth, either during or after a failed TMI maneuver. If it is used, the mission is a failure. Therefore, consistent with our philosophy of directing the mission assets toward the successful completion of the mission, we have chosen to use the mass that would be needed to provide such a vehicle to provide instead the required TMI backup capability in the form of a second engine so as to make an ECCV unnecessary. The strategy then, is to accomplish the TMI with 2 perigee burns. If one of the two nuclear engines fails prior to the second perigee kick, the mission could either be completed with the second engine (since the NTR engines are only used for TMI) , or the second engine could be used to bring the TASH down to an STS accessible orbit for recovery (the crew has sufficient provisions for even the longest STS response times). Alternatively, if one of the engines fails prior to the completion of the second perigee burn, the remaining engine would be used to complete the TMI burn. If there was a complete failure of the TMI stage during almost any portion of the TMI burn sequence (including all but the final 300 m/s of the 1000 m/s post-escape velocity increment), the combination of the descent stage's propulsive capability (700 m/s, including landing, midcourse, and post aerocapture periapsis raise ΔV's) and the aerobrake would again permit the TASH to be brought down to an STS accessible orbit for recovery of the crew.

Once the TMI and mid-course burns have been successfully completed, the TASH is targeted for an aerocapture pass at Mars. During the first 90% of the outbound flight, several options, including free-return aborts and powered fly-by maneuvers can be undertaken. However one the lander has been targeted for an aerocapture trajectory (typically several days prior to aeroentry), the options of a free-return or powered fly-by trajectory abort back to Earth become increasingly tenuous. At some point, on the order of several hours to one day prior to aerocapture, the ability to perform any trajectory abort is lost completely. Thus, once the aerocapture maneuver is begun, the concept of a trajectory abort is inapplicable.

Since in the Mars Semi-Direct (as in the Direct) mission plan, a rendezvous in Mars orbit prior to descent is not required, the accuracy of the capture orbit is unimportant, so long as the inclination of the orbit is such that it permits access to the surface site (i.e. the inclination of the capture orbit must be greater or equal to the latitude of the desired landing site.) With this in mind, so long as the crew captures into an orbit around Mars, the crew will be able to descend to the surface outpost that was delivered in the previous opportunity. (This relaxation of aerocapture accuracy requirements translates into a relaxation of aerocapture guidance, navigation and control requirements, significantly enhancing the attractiveness of aerobrake technology for the Mars orbit capture maneuver in our scenario.) If the aerocapture maneuver is unsuccessful to the point that the TASH will not capture into orbit, the crew could use the propulsive capability of the lander (up to 700 m/s) to augment the performance of the aerobrake. The crew might now be unable to descend to the surface in the TASH, but they would be captured into orbit around Mars.They would then have two potential options. first, following the crew out to Mars in the same opportunity would be an ERV with its TEI stage and a MAV/lander combination. Either of these two vehicles, or the ERV already in orbit around Mars, could be targeted in orbit with the disabled TASH. The crew could then use the MAV/lander to descend to the surface (possibly taking some consumables or other cargo from the TASH with them) and complete the baseline mission, albeit with a reduced surface habitation capability. Alternatively, the crew could remain in orbit and return in either of the ERVs, after 600 days in orbit. Either the MAV on the surface or the one on its way to Mars could bring its capsule to the ERV to provide it with a Earth crew capture vehicle.

However, since a safe haven and the possibility of completing the mission successfully exist on the surface of Mars, clearly the best option is to go there. The elimination of the need for a Mars orbit rendezvous prior to descent thus represents a major addition to mission safety. The surface rendezvous plan used in the Semi-Direct (as in the Mars Direct) mission then has several levels of backup to assure mission success. First of all we have the advance characterization of the site by 2 years of local robotic exploration out of the MAV (or the Mars Direct ERV), with placement of a transponder on the best possible landing site identified in the vicinity. The MAV also mounts a radio beacon much like an ILS transmitter at an airport giving the crew exact position and velocity data during approach and terminal landing. It may be noted that both Viking landers touched down within 30 km of their targeted sites without active guidance. With the aid of a feedback targeting control system and a guiding radio beacon, the landing should be within a few meters of the targeted point. However if the landing should prove inaccurate by tens or even hundreds of kilometers, surface rendezvous can still be achieved through the use of the pressurized methane/oxygen internal combustion driven ground rover carried in the hab, which has a one-way surface range of up to 1000 km. Because the crew has landed in a full habitat, and not a short duration small landing vehicle, they have the ability to support themselves for a long period of time if they should land in an isolated location, and therefore a third and fourth level of backup are also available. As the third level, if the landing rendezvous fails by distances of planetary dimensions, the second MAV following (by several months) the manned hab to Mars can be redirected to the manned landing site. As a fourth level of backup, the entire crew has been landed on Mars in a hab with enough supplies for a 4 year surface stay. If all else fails, they can just tough it out and wait for the next launch window when more supplies and another MAV can be sent out to them.

Because they use in-situ propellant for ascent, neither the Mars Direct nor Semi-Direct plans have the capability for abort-to-orbit during descent. However it is extremely doubtful that any lander, fully fueled for ascent though it might be, could really ascend successfully to orbit by taking off from a aeroshield buffeting its way at hypersonic speeds through the Martian atmosphere.

A Lunar Base Built by Mars Semi-Direct Hardware

While the Moon need not be a steppingstone to Mars, it is certainly the case that a properly designed piloted Mars mission system architecture will contain many elements that can also be used to perform Lunar missions. Since the Moon is a valid destination for explorers in its own right, commonality of Lunar and Martian systems is valuable regardless of whether the Lunar program is conceived of as existing prior to the commencement of Mars operations or afterwards (i.e. in the same manner as Skylab exploited Apollo hardware to create a space station). In the case of the Mars Semi-Direct baseline mission plan we have outlined above, it can be shown that a subset of the Mars mission hardware is almost ideally adapted to provide a good Lunar transportation system.

A Mars Semi-Direct derived Lunar mission would be conducted as follows: A single launch of a 120 t to LEO HLV would be used to lift a standard Mars NTR stage and modified versions of the MAV and ERV hab, together with their fueled CH_4/O_2 stages to orbit. (i.e. similar to a Mars Semi-Direct cargo launch but without aeroshells, Mars lander stages, or ISRU plant. The ΔV required to move a payload from LEO to Low lunar Orbit (LLO) is about the same as that need for TMI, and so a total mass of about 59 tonnes can be so inserted into LLO. This mass breaks down as follows:

ERV Hab	15 tonnes (Serves as Lunar surface hab)
TEI Stage	15 tonnes (Used to land ERV on Moon)
MAV	29 tonnes (Includes 21.5 t prop and 0.5 t augmented life support)
Total	59 tonnes

After Lunar orbit capture the NTR stage is expended and the wet MAV and ERV land separately, but at nearby locations on the Lunar surface. The TEI stage, which in the Mars mission application, has the capability of pushing the 15 t ERV hab plus the 5 t MAV capsule through a 1.7 km/s Trans-Earth Injection ΔV, in this application is used to perform the 2.0 km/s ΔV required to land the ERV hab on the Moon. The MAV (including ascent stage), with its drymass increased to 7.5 tonnes to include landing struts and its propellant offloaded from its full 24 tonnes down to 21.5, still has the capability to perform a ΔV of 5 km/s. This is sufficient for it to performing a landing on the Moon from Lunar orbit, and then, after an indefinite duration surface stay, perform a direct return to Earth from the surface of the Moon. The crew can thus ride out to the Moon in the MAV docked to the ERV, land in the MAV, live on the Moon in the spacious ERV hab, and then return to Earth in the MAV. Each subsequent mission leaves an ERV hab on the surface of the Moon, leading to the build up of either a major central base or an exploratory string of small outposts.

Thus we see that if Mars Semi-Direct is adopted, essentially no new hardware need be developed to create a substantial Lunar exploration capability.

Evolution of Expanded Mars Capability

The Mars Semi-Direct architecture is structured so as to create an incremental expansion in surface capability with each mission, as each mission leaves its primary habitat, two 12 kWe power units, an ISRU unit, 5 tonnes of science gear, 2 pressurized rovers and 4 unpressurized rovers on the Martian surface. This mode of operation leads naturally to the development of either a large central base, several medium sized bases, or numerous small outposts on the surface of the planet. The exploration and settlement capability of such a surface network can then be dramatically expanded by three modest technological developments, to wit the development of hardware to extract water from the Martian soil or atmosphere, the establishment of greenhouse agriculture on the Martian surface, and the modification of the MAV with the addition of a set of landing gear and aero protection to its ascent stage, making it a reusable surface to orbit ferry and long distance ballistic hopping vehicle.

Water exists on Mars in the form of permafrost, ice, hydrates, and water vapor, and the ability to extract it from any of these sources, while not needed for initial missions, offers prospects for open-ended enhancement of human capabilities on Mars. Access to local water eliminates the need to import hydrogen from Earth. By using the chemical synthesis plants to combine it with the readily available CO_2

atmosphere, every tonne of water extracted from the Martian environment can be turned into 2.9 tonnes of CH_4/O_2 bipropellant. By combining it with atmospheric CO_2 in an inflatable greenhouse, every tonne of water can be turned into 1.7 tonnes of dry plant material and 1.8 tonnes of oxygen. If each mission is allocated an expanded allocation (see below for why) of 72 tonnes of CH_4/O_2 for MAV and rover use, and 4 tonnes of dry plant material produced in the greenhouse is considered to be the equivalent of 1 tonne of combined whole and dry food transported from Earth, then the entire requirement for propellants and consumables for the surface and ascent part of the mission of a 4 person crew can be met by the extraction of 48 tonnes of local water. (This is the equivalent of a block of ice 3.8 meters on a side)

The transformation of the MAV from an expendable ascent vehicle into a reusable ferry and ballistic hopper allows for the elimination of the MAV surface cargo delivery mission on each "A" type cargo (ERV) launch. This not only saves money, by the elimination of a lot of expendable hardware from the mission, it allows a 40% expansion in the Earth return habitation mass, which in turn will allow the ERV to accommodate a crew of 6. This would not require a redesign of the ERV hab, which is a volumetrically large, lightweight structure in any case, but simply requires filling the ERV hab with more consumables, life support equipment, and adding extra life support equipment to the Earth crew capture vehicle. Since by this time in the system evolution, a large number of habs will be situated on the Martian surface, all consumable required to sustain surface crews will be produced on Mars, and much flight and surface operations experience will have been acquired, it will (at last) be desirable to expand the surface contingent. This will be possible simply by trading some of the food in the standard TASH for washing water, allowing it to house a crew of 6 on an outbound transit. The crew will stay over on Mars an extra synodic period, increasing the surface tour of duty from the earlier missions' 1.5 years to a new standard of 3.7 years. Since in this case crews delivered every two years will overlap their sojourns, the net result will be that with just two launches every other year, a total crew complement of 12 astronaut explorers will be sustainable on Mars.

(If no increase in surface complement is desired, the ERV could be kept at its standard size and the MAV/hopper used to take about 10 tonnes of cargo from it for surface delivery. This could be done either by cargo transfer into the MAV/hopper capsule from the ERV, or by switching out the capsule in the MAV/hopper containing a crew during their return ascent to the ERV with a MAV capsule loaded with cargo which was flown out to Mars with the ERV. Alternatively, the ERV could deliver no cargo, but the propellant load in the (normally offloaded) TEI stage increased, allowing fast transfers for the crew on the return leg of the mission)

However much more important than such enhancements to the standard mission profile is the fact that a reusable MAV would give the crew of the mission global mobility. Assuming that adding the landing struts and aero protection to the MAV caused its dry mass to increase by 1.2 tonnes (20% of the dry mass of the baseline MAV), then with 24 tonnes of CH_4/O_2 propellant, the modified MAV hopper would still be capable of generating a ΔV of 5 km/s. (This reduction of performance compared to the 5.5 km/s capability of the expendable MAV is taken account of in the analysis of increased ERV capabilities given in the preceding paragraph). With such a ΔV, the MAV would be able to take off from anywhere on the planet, reach orbit, and then come down and land anywhere on Mars. Crews could thus transfer from one base to another separated by continental scale distances in a matter of hours. The vehicle would also be able to take off, land at a site 1000 km away, and then take off and land again[11]. Round trip exploration sorties from a central base of 1000 km would thus be possible, double the effective range of the ground rovers.(assuming that the ground the MAV flies over is passable by rovers in the first place), thus multiplying by at least a factor of 4 the area available for exploration by the crew. If a network of multiple bases is employed, such a system would make accessible to any crew all terrain within 1000 km of any of the bases. Such a capability would represent an enormous increase in exploratory freedom for the crew, and as such would provide a terrific multiplier of overall mission effectiveness. Since 24 tonnes of CH_4/O_2 are needed for each maximum distance flight, only 8 tonnes of water would have to be mined to produce the propellant required for each such sortie.

Once sufficient numbers of transfer and surface habs have been delivered to Mars, the next step in system evolution would be shift the mission architecture into a modified Mars Direct mode, in which the crew flies out to Mars in the enlarged (28 tonne, 6 crew) ERV, lands in it, operates for 3.7 years on the surface, refuels and re provisions the ERV on the surface, and then returns direct from the surface to Earth. By employing this mission mode, our standard launch rate of two HLV launches every other year will allow two 6 person crews to be rotated each opportunity. Given the crew overlap on the surface which will occur because of the 3.7 year stay times, the total crew complement on the surface will increase to 24. The only hardware innovations required to take this step is to create a new CH_4/O_2 ascent stage that can contain 160 tonnes of propellant and use it as the first stage of a two-stage ERV, with the second stage provided by an enlarged (38 t propellant) MAV ascent stage. If no hydrogen is imported from Earth, then 70 tonnes of water would have to be extracted from Mars to provide the necessary return propellant for this vehicle. The first stage of this vehicle could be given 3 tonnes of aero protection and landing gear and attached to a 10 tonne cabin to form an enlarged reusable ballistic hopper. Such a large hopping vehicle would be able to take crews of 4 on month-long round trip excursions of up to 3000 km from any base, thereby increasing surface access by another order of magnitude beyond that possible with the small reusable MAV/hopper. Positioned at remote sites, the large hopper could use its reserves of propellant to support operation from its location of regional sorties by not only rovers, but small MAV/hoppers as well.

(Alternatively, an extended range (3000 km round trip) MAV/hopper could be built by combining a CH_4/O_2 stage with a 80 t propellant capacity with a 5 t MAV capsule. Such a vehicle would be capable of lifting the 8 tonnes of consumables required to support a 6 crew ERV through a return transit. With such an operational capability emplaced at Mars, the crew could ride out to Mars in an ERV, park in high orbit, be picked up by a (small or extended range) MAV/hopper and delivered to the surface, conduct a surface mission, and finally be delivered together with their Earth-return consumables back to an orbiting ERV by an extended range MAV/hopper. As in the case of the Mars Direct evolution described above, such a system would allow a crew of 6 to be rotated to Mars and back by a single HLV launch. This mission mode requires less ISRU than the Mars Direct evolution, and a more modest evolution of hardware. However a mission-critical Mars Orbit Rendezvous is required before the crew can land, and so the fundamental abort-to-surface mission safety capability both the Mars Direct and Semi-Direct architectures is lost. Furthermore, the refitting of a used ERV in this mission mode must be done on-orbit by the return crew alone, instead of on the surface where the full capabilities of the base and the skills of its large crew complement are available to support the refit. If a refit crew based on the surface finds difficulties, they can just walk home to the hab, have a cup of coffee, and try again the next day with new tools, new ideas, or even a new ERV (as due to mission staggering, there will always be two on the surface at any time.) If a crew engaged in an orbital refit gets stymied, they have to go all the way back to the surface, and must perform another launch and MOR before they can try again. For these reasons, a Mars Direct evolution of the Semi-Direct mission is considered superior to a double MOR evolution.)

The large Mars Direct-derived ballistic hopper, extended range MAV/hopper and even the small MAV/hopper would also be able to deliver substantial cargoes one-way point-to-point across Mars, as shown in Fig. 8. By exploiting this capability, a large surface base where food is grown could service smaller exploration outposts scattered across Mars, and technological assets could be shifted around the planet as needed.

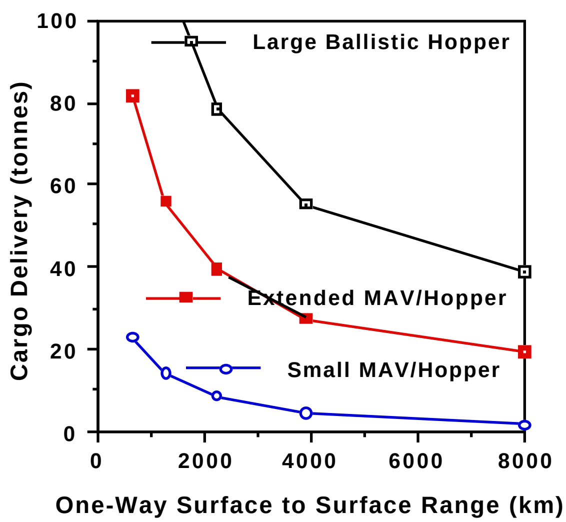

Fig. 8 Surface to surface cargo delivery capability of the large ballistic hopper and the extended and small MAV/hoppers. The large ballistic hopper can deliver 50 tonnes to a location 4000 km from its takeoff point.

With the implementation of these steps of system evolution, a large and self-sustaining crew will exist on Mars, operating at a high level of activity out of a network of strategically placed bases possessing abundant supplies of food, water, and power, scientific facilities and habitation space. This network of bases, created solely through the use of near-term technology and sustainable by an average terrestrial launch rate of 1 HLV per year, will support a set of vehicles that will give the explorers complete local, regional, and global access. The Martian frontier will be wide open.

Conclusions

In conclusion we find that the use of direct-throw mission strategies combined with utilization of in-situ propellants allows for simple , robust, cost-effective, and coherent plans for Mars Exploration. By eliminating the need for construction on-orbit of futuristic mega-spaceships, such a strategy drastically reduces up-front development costs and technology challenges of the required flight systems, thus enabling an early commencement of human Mars exploration. Furthermore, in contrast to accelerated approaches that employ brute-force means, the use of in-situ resource utilization right from the start of the program allows missions to be conducted in such a way as to minimize cost and maximize exploratory return for each recurring mission.

The 50 kWe power requirements for the manned Mars Direct propellant production can be met by near term surface nuclear electric systems, and in the case of the Semi-Direct mission, by currently existing 10 kWe Topaz or near-term DIPS units. Near-term physical chemical life support systems, using processes nearly identical to the in-situ propellant production are found to optimal from the point of view of mass and power, and combined with stockpiles of consumables that can be produced in-situ. on the Martian surface, provide a robust life support architecture adequate to meeting the challenge of a 2.5 year roundtrip Mars mission. We also find that the use of the transportation system/surface architecture we describe allows for flexible and rapid evolution to either a permanently staffed large central base or a string of widely dispersed but surface-to-surface transportation linked exploratory outposts spread over wide areas of the Martian surface.

We therefore recommend that a space transportation architecture similar to what we have described be made the baseline for NASA human Mars exploration planning, and that appropriate resources be allocated for the rapid development of in-situ propellant production and the other key technologies required.

Acknowledgment

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References

1. R. Zubrin and D. Baker, "Humans to Mars in 1999," Aerospace America, August 1990.

2. D. Baker and R. Zubrin, "Mars Direct: Combining Near-Term Technologies to Achieve a Two-Launch Manned Mars Mission," JBIS, Nov. 1990.

3. R. Zubrin, D. Baker, and O. Gwynne, "Mars Direct: A Simple, Robust, and Cost-Effective Architecture for the Space Exploration Initiative," AIAA 91-0326, 29th Aerospace Science Conf., Reno NV Jan.1991.

4. M. Duke, Private communication, Oct. 1992.

5. D. Weaver, "Mars Study Team Reference Mission Overview," Presented at Mars Working Group conf., NASA Ames Research Center, May, 1993.

6. T. Stafford et-al,"America at the Threshold: Report of the Synthesis Group on America's Space Exploration Initiative," U.S. Gov. Print. Off. May 1991

7. K. Joosten, Bret Drake, D. Weaver, and John Soldner, "Mission Design Strategies for the Human Exploration of Mars," IAF-91-336, 41st Congress of the International Astronautical Federation, Montreal, Canada, Oct. 1991.

8. R. Zubrin and T. Sulmeisters, "The Application of Nuclear Power and Propulsion for Space Exploration Missions," AIAA-92-3778, AIAA/ASME Joint Propulsion Conference, Nashville, TN, July 1992.

9. A. Cohen et al "the 90 Day study on the Human Exploration of the Moon and Mars," U.S. Government Printing Office, 1989.

10. A. Gonzales, L. Harper, E. Dunsky, and B. Roberts, "Mars Surface Mission Life support

Summary," Presented to Mars Exploration Workshop II, NASA Ames Research Center, May 24, 1993.

11. R. Zubrin, "Long Range Mobility on Mars," JBIS, Vol 45, p.203-210, May 1992.