N93-14016

LUNAR STEPPING STONES TO A MANNED MARS EXPLORATION SCENARIO

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The initial trips to Mars by humans will be the first real severing of our dependence on Earth's environment. Common sense dictates that a human departure from Earth measured in years, to explore a distant planet, requires systems, techniques, and operations that have solid credibility proven with space experience. The space test and verification experience must occur with Mars-like conditions but under proving-ground conditions with good instrumentation, close monitoring, and fast emergency recovery capabilities. The lunar environment is the only arena that satisfies the requirements of a space planetary proving-ground. The objective of this scenario is to demonstrate a program planning approach that has human presence at Mars as the goal but, prudently, capitalizes on manned lunar project facilities, operations, and experience to enable a safe journey for the first Mars crew. The emphasis in lunar application objectives is to perform productive science and resources exploitation missions. Most of the Mars mission aspects can be proven in the lunar environment providing "stepping stones" to conducting the first human mission to travel to Mars and return safely to Earth.

SCENARIO STRATEGY

The Mars trip is measured in years, which presents the major challenge in implementing the scenario missions. We do not have space systems now that can perform and sustain human life away from our home planet for years. In addition, immediate help will not be available from experts on Earth for emergencies. The distance is so great that communications can take 15 to 20 minutes to receive a response. We have been to the Moon and the successful achievement of the activities in the Apollo program was awesome. Many new systems and operations had to function perfectly in the lunar trips, but the path to Mars is much more difficult.

The strategic goal for this combined lunar-martian exploration scenario is to extend human presence to Mars, while also returning to the Moon, with applications emphasis on science and resources exploitation. The strategy for implementing this goal is to be conservative relative to risk, bold in the extent of the Mars vehicle exploration capability, and cost effective in the use of common space systems and planetary resources. Because of the difficulties of the Mars objective, credible planetary systems, i.e., ones proven with extensive space experience, are required. That is, the systems used in the Mars journey must be ones with which the crew will be comfortable—like an "old friend" that has stood the test of time. The Moon can be used as a planetary proving-ground where systems common to Moon and Mars exploration are used productively and improved in design as a result of rigorous application. The plan is to use the safe (relative to the martian environment) lunar environment to learn planetary operations while conducting productive science and resource objectives. Based on this foundation of lunar experience, humans will separate from Earth for extended exploration at Mars. Building on the combined lunar and martian experience, planetary systems will continue to be developed, planetary resources utilized, and a human colony initiated on Mars.

The combined lunar-martian exploration scenario has been developed at a conceptual level. The general mission concepts for the lunar and martian flights are described in sufficient detail to identify the vehicles and major operations involved. A program of flights is synthesized to meet the goals of the scenario and developed into a flight schedule. An initial analysis has been performed to define the effort required to implement the scenario flight schedule. At this conceptual level, the support effort is measured in terms of the mass that must be delivered to low Earth orbit (LEO).

GUIDELINES AND ASSUMPTIONS

The central guideline for the scenario is to plan designs that exclude use of controversial technology leaps, minimize the Mars-bound vehicle initial weight prior to transmartian injection, use common systems, and provide schedule and configuration flexibility. The following assumptions are necessary to develop the combined lunar-martian exploration scenario:

1. A heavy lift launch vehicle is available for use to deliver approximately 100,000 kg per flight to LEO.
2. Chemical rocket engines are the baseline propulsion system for transplanetary propulsion and are assumed until specific trade analyses indicate a change is advantageous. Liquid oxygen and hydrogen are used in the engines for translunar and transmartian injection.
3. Artificial gravity habitation during transplanetary cruise is the baseline gravity habitation environment until trade analyses indicate a change is advantageous.
4. Aerocapture at Mars and Earth arrivals for savings in propellant is a baseline transportation technique until trade analyses indicate a change is advantageous. However, aerocapture must be flight verified to be as credibly safe as propulsive deceleration.
5. It is assumed that no significant water is discovered on the Moon.

6. Extensive operational applications of automated systems to control the manned spacecraft will be standard operating procedure.

7. Human planetary systems must be proven in rigorous operational use before application with human flight to Mars.

8. Human space flight in the lunar environment is sufficiently controllable to be safe for use as a planetary systems proving-ground.

9. Science objectives are pursued at the Moon on a noninterference basis with the planetary technology development objectives. In many cases, the two objective categories are mutually supportive.

10. Mars flights are conjunction class missions.

11. The Mars missions are sized to accomplish significant exploration on each trip.

12. It is assumed that Phobos is discovered to have materials usable for the production of propellant.

MISSION CONCEPTS

The mission concepts for the lunar and martian flights have many commonalities in the systems and operations to be performed. The flights in each planetary environment are generally defined in the following paragraphs.

Travel to the Moon is based on use of a reusable Orbit Transfer Vehicle (OTV). The components of the lunar flight concept are illustrated in Fig. 1. In this scenario, two OTVs are stacked with the payload mated to the second-stage OTV. A transportation staging node is required in LEO to assemble and launch the missions to the Moon. The LEO node consists of two Planetary Habitation Modules (PHMs) rotating about a central hangar to develop artificial gravity. Artificial gravity is used to gain experience for the Mars mission and to enhance propellant transfer. The first-stage OTV returns through the Earth's atmosphere using aerocapture techniques to return to the LEO node. The second-stage OTV and payload insert into a low lunar orbit (LLO). A variety of missions are conducted from this point in the generalized mission profile. The most common mission is the descent of a reusable Moon Flight Vehicle (MFV) to the lunar surface. On the lunar surface, crews perform science, construction, and resource exploitation work. They use surface transportation vehicles, both unpressurized and pressurized, to extend their range of operation. The Local Transportation Vehicle (LOTRAN) is unpressurized while the Mobile Surface Applications Traverse Vehicle (MOSAP) is pressurized and capable of long-range excursions. The MFV departs from the lunar surface to rendezvous with the OTV in LLO. The OTV carries the crew and/or payload through trans-Earth flight and aerocapture back to the LEO node. In another flight, the Mars Lander habitation module is delivered to the lunar surface and provides the first lunar outpost. Later, a permanent science outpost is constructed utilizing the PHM and other Mars-destined components. About this time, lunar oxygen is produced and used for all lunar descent and ascent flights. This phase of the scenario requires that Earth hydrogen be brought from the Earth and accumulated in an LLO propellant depot. The depot implementation is based on use of the PHM. The MFV is also used in LLO for moving between orbits and maneuvering space elements.

The Mars flight is a conjunction class mission. Departure is from the LEO staging node. The Mars mission vehicle crew quarters and operations center are in two PHMs implemented in an artificial gravity configuration. The Mars mission vehicle passes through the martian atmosphere upon arrival for an aerocapture transfer into a 24-hour elliptical orbit. The components of the Mars flight concept are illustrated in Fig. 2. Multiple Mars landings are included in each Mars trip. An expendable Mars Lander carries the crew and payload to the planetary surface direct from the 24-hour orbit using aerobraking and parachutes. In exploration visits of approximately 60 days each, crews perform science, construction, and resource exploitation work. They use the LOTRAN and MOSAP to extend their range of operation on the surface. The expendable Mars ascent stage takes the crew and payload to low Mars orbit. An MFV transfers from the Mars mission vehicle in the 24-hour orbit to the low Mars orbit to retrieve the surface crew and return to the Mars mission vehicle. The MFV is also used in independent flights to Phobos and Deimos where crews perform science and resource exploitation work. In later missions, PHMs are delivered to the martian surface to facilitate extended human presence. Development of oxygen on Phobos is included in the final stage of this scenario. The return to Earth is a continuation of the conjunction class mission. On approach to Earth, the crew transfers to an aerocapture module and separates from the large mass of the mission vehicle. The Mars mission vehicle is expendable and continues beyond Earth while the crew returns to LEO.

LUNAR STEPPING STONES

In this scenario, we return to the Moon and use it as the proving-ground for planetary technologies and experience that enable a safe journey to Mars. The lunar achievements providing

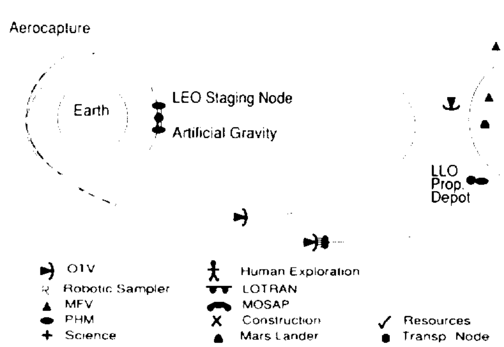

Fig. 1. Lunar flight concept.

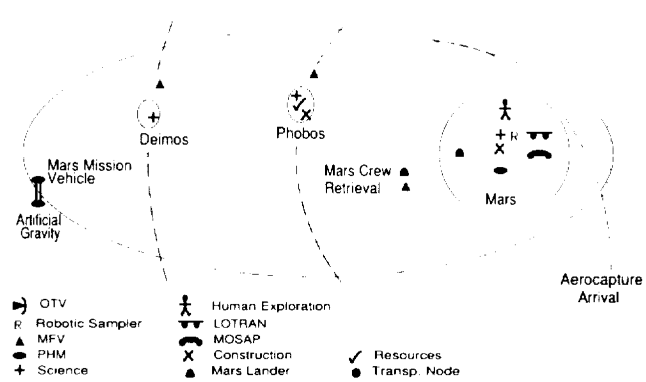

Fig. 2. Martian flight concept.

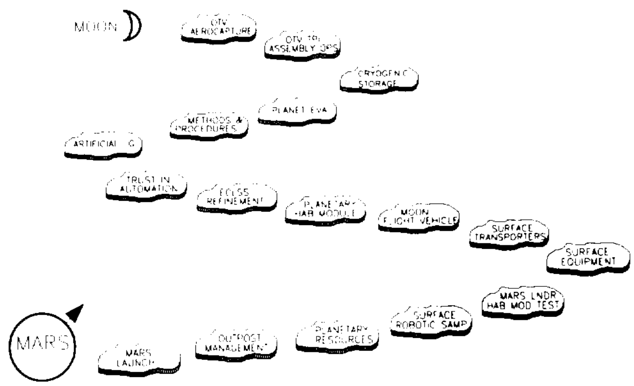

Fig. 3. Lunar stepping stones to Mars.

stepping-stones in the path to Mars are illustrated in Fig. 3. These steps common to both the lunar and the martian exploration fall into two broad categories, systems and operations. Both categories are identified in the following paragraphs, starting with the one that is less often considered, but is potentially more critical.

The common operations, methods, and procedures that can be learned in the lunar environment and must be mastered before attempting Mars exploration are (1) in-space planetary vehicle assembly and transplanetary injection operations, (2) EVA-based planetary field operations, (3) on-site planetary science and sample analysis methods and procedures, (4) planetary construction methods and procedures, (5) artificial gravity environment verification and operations adaptation, (6) trust in automated and computer-controlled systems operations, and (7) planetary outpost site management techniques and procedures.

Planetary systems having common systems design criteria for performance in the lunar and martian missions are (1) aerocapture structures, materials, and vehicles, (2) cryogenic propellant in-space storage and transfer systems, (3) artificial gravity systems, (4) life support systems refinements, (5) planetary habitation module, (6) Moon Flight Vehicle, (7) Local Surface Transportation Vehicle, (8) Mobile Surface Applications Traverse Vehicle, (9) surface equipment for science and construction, (10) Mars lander habitation module, (11) planetary surface robotic sampler, and (12) planetary resources plant equipment.

FLIGHT SCHEDULE

Using the strategy of this scenario, the stated assumptions, the space elements identified in the mission concepts, and the common requirements in the stepping-stones, a scenario flight schedule has been developed. The schedule, which includes calendar years 2001 through 2025, is provided in Fig. 4. However, prior to 2001, a number of important precursor missions have occurred. Automated missions have been flown to the Moon and Mars. The MFV has been flown in LEO with crews for flight test and verification. The PHM has been flown for one year to verify systems design and operation in LEO using a zero-gravity mode.

The sequential flow of flight activity shown in Fig. 4 begins with the orbiting of a second PHM and artificial gravity systems to combine with the initial PHM. This PHM configuration is flown for one year as an experiment and verification of artificial gravity habitation. Also in 2001, the first humans return to the lunar surface using the MFV in the final flight verification of the vehicle. At the conclusion of the one-year artificial gravity verification flight, the PHM configuration is expanded with additional systems from Earth into the LEO transportation staging node. In 2002, local lunar science is initiated and performed in a two-year series of MFV exploration flights. A four-year series of MFV outpost exploration flights begins in 2004 with the delivery of a Mars Lander habitation module to the lunar surface. During this period, a two-year operation of a lunar oxygen pilot plant is accomplished producing 2000 kg of liquid oxygen per month. In 2007, annual missions are started to the farside of the Moon to perform observatory objectives. The following year, a LLO propellant depot is established to store liquid hydrogen from the Earth in preparation for lunar flight operations using lunar oxygen. The oxygen production plant is delivered and constructed on the lunar surface in 2009 and starts production leading to 20,000 kg per month. The construction of a science outpost begins in 2008 and continues in operation with MFV support for the duration of the scenario. It is projected that the potential for exporting lunar resources will not occur until the closing of this scenario period.

The first Mars mission leaves on the 2007 opportunity. This first human flight will stress total environment investigation (four surface expeditions, human visits to Phobos and Deimos, numerous automated probes, and extensive orbit observations). The transportation system is designed to deliver a base to the surface of Mars over a long series of missions. It is, therefore, oversized for the first manned mission. A mission is not planned at the next conjunction class opportunity to allow adjustment to the first mission experience. Thereafter, a mission is flown at every conjunction class opportunity. The mission objectives are gradually expanded from local science, to regional science, to resources emphasis, and, finally, to preparing for a self-supported Mars surface base.

SUPPORT ANALYSIS

It is important to consider the impact on national resources of supporting a particular scenario. Since the scenario has been synthesized at a conceptual level, it is not possible to estimate the required support resources or dollar cost. An available measure of support impact that is closely related to the eventual cost budget is the mass required to be delivered to LEO to

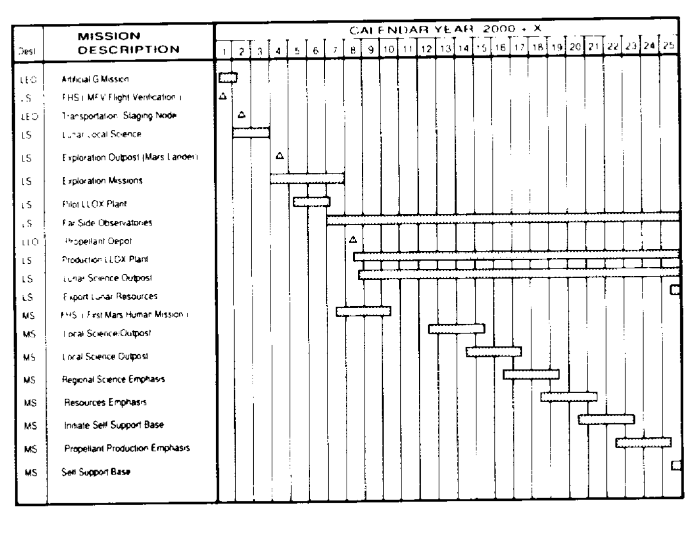

Fig. 4. Flight schedule for combined lunar-martian exploration scenario.

operate the scenario missions. The flight schedule provided in presentation form in Fig. 4 was developed in a computer spreadsheet with individual flights and estimated masses of the flight elements. The spreadsheet was designed to accumulate the masses by year and by various scenario elements. The resulting mass schedule has been summarized in Figs. 5-9. Figure 5 shows the payload mass delivered to the lunar surface on a yearly basis. The low mass in 2006 is an intentional gap to accommodate preparations for the first Mars mission. The high peak masses in the years 2004 through 2010 reflect the impact of establishing the initial lunar facilities. The bar chart in Fig. 6 requires special interpretation due to the methods used in the spreadsheet and the long duration of the conjunction class Mars missions. Each Mars mission vehicle stack is assembled in LEO over a two-year period. The Mars payload mass is entered on the schedule divided into the two years prior to arriving in Mars orbit. For example, the payload mass for the first mission in 2007 is approximately 500,000 kg. The line graph in Fig. 7 can be interpreted as showing two points. First, the surface payload mass for both the Moon and Mars are in the same order of magnitude. The second observation is that the lunar surface payload accumulation leads the martian payloads early when the lunar facilities are being established, but the later mass to establish martian surface facilities is greater. Two reasons for the greater martian mass are that the expendable landers are considered as surface payload and two martian bodies are receiving surface facilities (Phobos and Mars). Reusable landing vehicles are much easier to build for the Moon than for Mars due to the atmosphere. Figure 8 is a stacked bar chart that records the total annual mass delivered to LEO in support of this scenario. The bars identify the components due to each of the Earth orbit, the lunar, and the martian activities. The direct Earth orbit masses are relatively insignificant. The initial peaks in 2004 through 2009 are due to the combined requirements of the emplacement of the lunar surface facilities and the support of the first Mars mission. In later years, the annual mass for the Mars support appears to overshadow the lunar support. However, Fig. 9 shows that the apparent imbalance is less when viewed over a longer time period. This line graph plots the cumulative mass delivered to LEO in support of this scenario. In this view, the lunar and the martian accumulated LEO mass can be seen to be in the

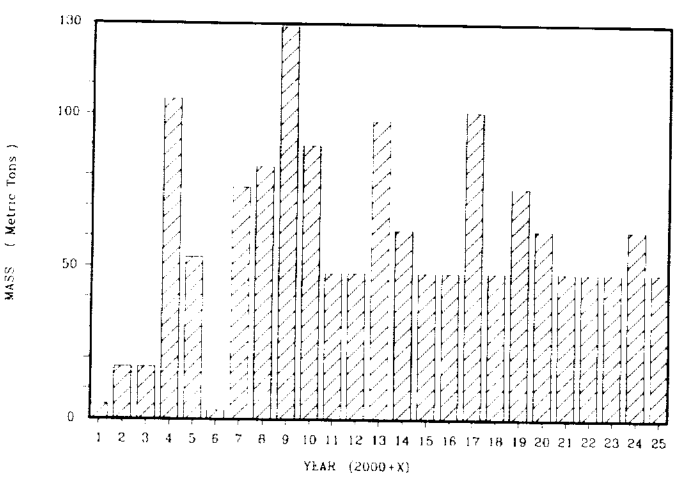

Fig. 5. Annual payload mass to lunar surface.

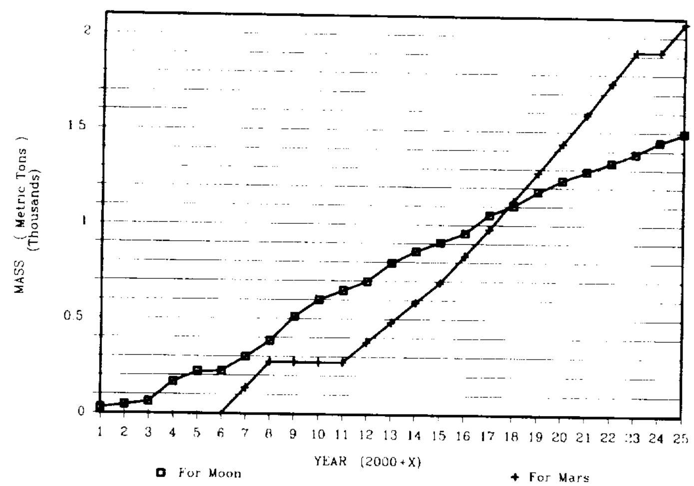

Fig. 7. Cumulative mass to planet surface.

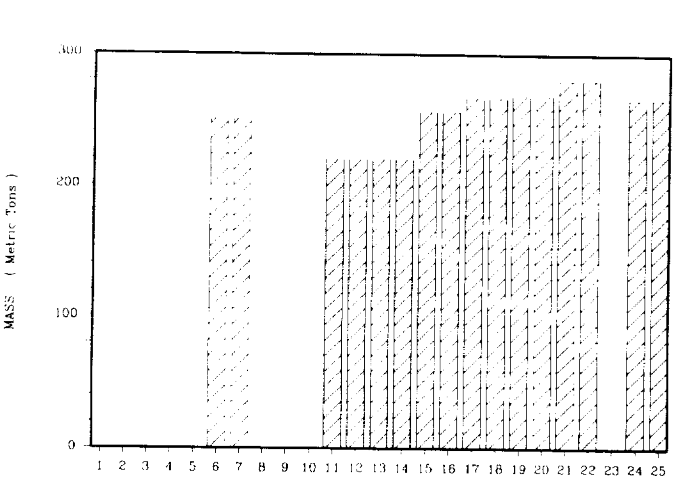

Fig. 6. Annual Mars orbit payload mass launched to LEO.

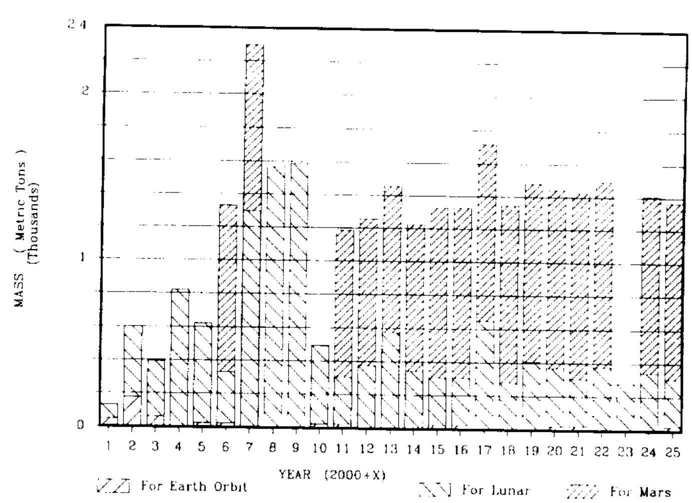

Fig. 8. Annual mass required in LEO.

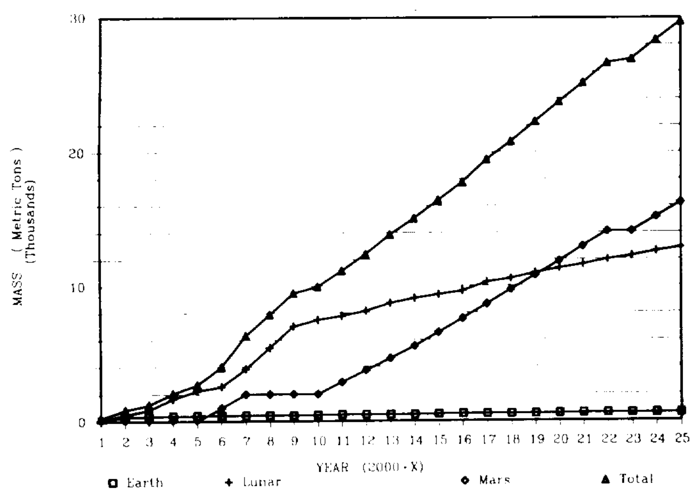

Fig. 9. Cumulative mass required in LEO.

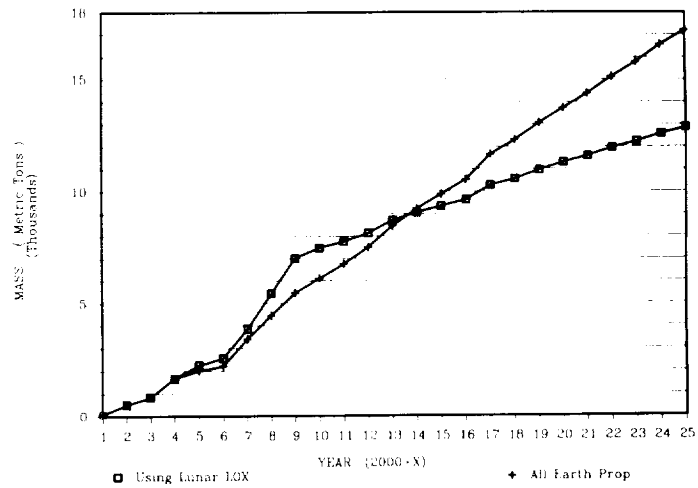

Fig. 10. Reduction in cumulative mass required in LEO using lunar oxygen.

same order of magnitude. In fact, it is 2019 before the martian numbers exceed the lunar support. An additional point is that the lunar support LEO mass required has been reduced through the use of lunar resources while the martian resource usage benefit has not yet come into operation.

It is important to reduce the mass required to be delivered to LEO in support of this scenario in order to lower the program cost. The required mass in LEO can be reduced by various approaches; as an example, the amount of LEO mass reduction can be shown for a method used in this scenario. The plant producing oxygen on the lunar surface begins operation in 2009. Figure 10 plots data indicating the reduction in cumulative mass required in LEO when using lunar oxygen. The plot for the scenario using lunar oxygen (squares) indicates a high rate of mass accumulation until 2009 while related facilities are implemented. At this point, lunar oxygen utilization begins and a knee in the plot verifies a reduced rate of LEO mass accumulation. The plot for the same scenario application missions, but no use of lunar oxygen or implementation of facilities related to lunar oxygen production is marked with plus symbols. The plot demonstrates that there is less LEO mass required in the early years, but by 2014 the cumulative savings when using lunar oxygen cause the plots to diverge. Other potential approaches to reducing required mass in LEO include lunar oxygen delivered to LEO, Phobos oxygen production and use at Mars, martian oxygen production and use at Mars, martian mission departure from the lunar vicinity, and use of more advanced propulsion systems. These other approaches should be investigated, but were not developed in this scenario. The development of Phobos oxygen in the closing years of the scenario time period was included, but the beneficial effects would not be realized until the self-supported Mars base phase following this scenario.

SUMMARY

In summary, a combined lunar-martian scenario has been developed. The goal of the scenario is to extend human presence to Mars and to return with humans to the surface of the Moon for extensive applications in science and planetary resources exploitation. The common links between lunar and martian exploration have been described and referred to as lunar stepping stones in the path to Mars. A methodology has been developed for planning, implementing, and assessing planetary exploration scenarios. The impact of implementing the missions in the scenario has been reviewed in terms of the mass required to be delivered to LEO to support the scenario operations. The data demonstrate that these lunar and martian activities require resources on the same order of magnitude. It has also been shown that simple use of lunar oxygen can provide visible reductions in required program resources.

It is imperative that the first human journey to Mars return safely to Earth. This success requires that all systems and operations be proven in previous, repetitive program activities. The Moon is the only suitable planetary proving-ground and provides exciting opportunities for exploration on its own merit. A program to develop the described lunar stepping stones to Mars should be developed in more detail. The Mars trip may be the challenge, but the success of the journey will be determined on the Moon.