IN SITU PROPELLANT PRODUCTION: ALTERNATIVES FOR MARS EXPLORATION

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PREFACE

This study was completed between May 1990 and April 1991 by members of the Advanced Planning and Analysis Division of Science Applications International Corporation. The study was sponsored by the Space Propulsion Technology Division of NASA Lewis Research Center, and conducted as a task order under contract number NAS3-25809.

SAIC acknowledges the contributions of several reviewers who offered valuable insight and commentary on recovery of raw materials, in situ processing, and propellant utilization strategies. Dr. Robert L. Ash of Old Dominion University examined our characterization of propellant recovery and processing options, and suggested key areas for technology development and early testing of candidate processes. Mr. James R. French of JRF Engineering Services provided a systems-level critique of the assessment approach and alternative utilization strategies, and reviewed the results of performance trades. Dr. Kumar Ramohalli of the Center for Utilization of Lunar and Planetary Resources at the University of Arizona reviewed the infrastructure assessment approach that we proposed, and offered suggestions on presentation of this material. We also appreciate review of the final manuscript and editorial suggestions by Terri Ramlose of SAIC.

The study team thanks Diane Linne, the NASA Task Leader, Michael Meyer, and other members of the NASA/LeRC technical staff for their guidance and discussions of this work.

Table of Contents

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1. SUMMARY

Current planning for the Space Exploration Initiative (SEI) recognizes the need for extraterrestrial resources to sustain long-term human presence and to attain some degree of self-sufficiency. As a practical matter, reducing the need to carry large supplies of propellant from Earth will make space exploration more economical. For nearly every round trip planned with conventional propulsion, the actual payload is only a small fraction - perhaps 10-15% - of the mass launched from Earth.

The reference propulsion system for lunar and Mars exploration is an advanced design that burns liquid oxygen/hydrogen (LOX/H_2) bipropellant at a high specific impulse. However, improved engine performance with chemical bipropellants is not by itself sufficient to capture the flight profiles and payloads required to send humans to Mars. Using propellant from Earth, the baseline space transportation system also requires the use of aerobraking techniques to reduce capture impulses (Report of the 90-Day Study 1989). After a lunar surface base is established, LOX produced on the Moon would be combined with hydrogen fuel from Earth for use in lunar ascent and descent propulsion. However, the potential leverage of this in situ propellant production (ISPP) approach is limited by continued reliance on the need to bring adequate hydrogen supplies from Earth; moreover, applications beyond near-lunar space may not be efficient.

The objective of this study was to analyze the potential application for SEI missions of propellants made exclusively from lunar or martian resources. Using such propellants could minimize or eliminate the cost of carrying propellant for surface excursion vehicles and return transfers through two high-energy maneuvers: Earth launch and trans-Mars injection. Certain chemical mono- and bipropellants are candidates for this approach; they could be recovered entirely from in situ resources on the Moon and Mars, without requiring a continuing Earth-based resupply of propellant constituents (e.g., fuel to mix with a locally obtained oxidizer) and, perhaps, with minimal need to resupply consumables (e.g., reagents or catalyst for process reactions). A complete assessment of the performance potential of these propellants must include the requirements for installation, operation, maintenance, and resupply of the chemical processing facility.

Many candidate processing schemes have been studied for manufacturing from raw materials on the lunar surface. Most of this work emphasized recovering oxygen for life support and for bipropellant oxidizer. Some of these studies have also examined extraction of additional lunar resources using the same process, often with emphasis on elements such as aluminum and iron that could be useful in lunar construction. Several of these candidate processing concepts were assessed as part of this study; they are divided into two broad groups: processes based on terrestrial counterparts, and "space-based" processes.

Terrestrial mining and resource extraction methods use readily available resources to expedite processing or to reduce cost; on Earth, the abundant supplies of oxygen, hydrogen, carbon, and water are used extensively. Because these resources are not readily available on the Moon, lunar processes derived from terrestrial experience must be modified to conserve these and any other reagents that must be supplied from Earth. Other methods have been proposed that do not require reagents, but make use of thermal or electrical energy to separate various constituents of lunar regolith. These processes could be considered "space-based": they are not the most economical choices for processing on Earth, but they may offer advantages in space, where energy is more abundant and cheaper to provide than reagents. Experience with these processing candidates is very limited, and materials technology advances are likely to be required even to test these processes in a relevant environment.

Thirteen lunar-based processing candidates (Table 1-1) were selected for detailed consideration. Since this study included candidate propellant constituents that could be combined with LOX, the amounts of recovered LOX and metal for a metal gel must be balanced to meet the desired propellant mixture ratio. Processes typically recover much more oxygen than a specific metal, so process output requirements were

TABLE 1-1
CANDIDATE LUNAR PROPELLANT PROCESSES

Process	Resources Recovered	Potential Amounts Obtained per 100 t O2
Processes based on terrestrial counterparts		
- Hydrogen Reduction of Ilmenite	Fe, O2	350 t Fe
- Carbothermal Reduction	Si, O2	58 t Si
- Hydrogen Sulfide Reduction	Fe, O2	125 t Fe
- Carbochlorination	Al, Si, O2	48 t Al, 50 t Si
- HF Leach	Al, O2	16 t Al
- Reduction by Li or Na	Si, Fe, Ti, O2	70 t Si, 45 t Fe, 10 t Ti
- Reduction by Al	Al, Si, O2	42 t Al, 44 t Si
- Direct Fluorination of Anorthite	Al, Si, O2	48 t Al, 50 t Si
"Space-based" Processes		
- Magma Electrolysis	Fe, O2	350 t Fe
- Fluxed Electrolysis	Al, Si, Fe, O2	21 t Al, 62 t Si, 40 t Fe
- Solar Wind Gas Extraction	CH4, CO, O2	69 t CH4, 82 t CO
- Vaporization/Fractional Distillation	Al, Si, O2	19 t Al, 58 t Si
- Selective Ionization	Al, Si, Fe, Ti, O2	17 t Al, 50 t Si, 32 t Fe, 8 t Ti

scaled from the amount of metal required for a selected monopropellant mixture ratio. Process descriptions begin with a feedstock and end with separation of resources (Figure 1-1). In many cases, lunar raw material must undergo some mechanical or chemical beneficiation step to isolate a specific mineral or chemical compound that will be the feedstock to the process. Excavation and beneficiation, product collection and storage, and power system requirements for each step were also included in this analysis.

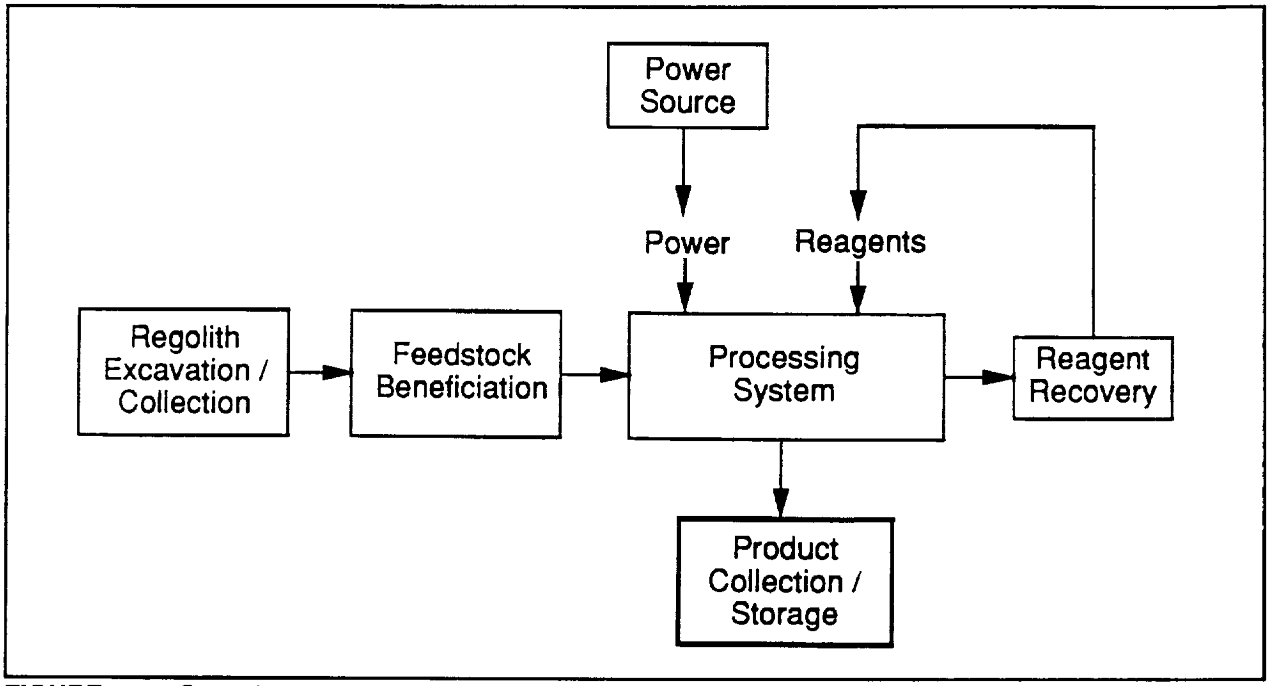


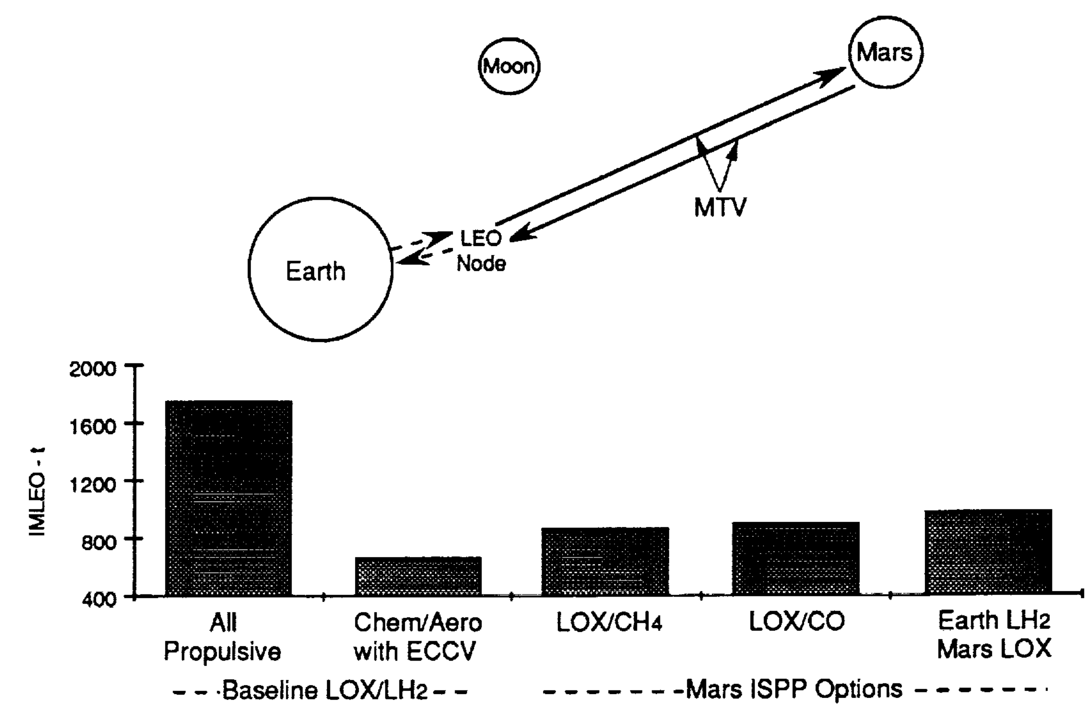
FIGURE 1-1: Generic Process Flow Diagram

None of the processes has been developed beyond NASA/OAET readiness level 4, emphasizing that more research is needed to assess performance of the many alternatives for lunar propellant production. Although much work has been done at the conceptual level, only three candidates, hydrogen reduction, carbothermal reduction, and HF leach have been demonstrated on breadboards in a laboratory environment. Processes requiring isolation of a specific lunar mineral, oxide, or silicate rely heavily on the development of a feasible beneficiation strategy. Beneficiation technology remains largely unstudied. The problem of isolating ilmenite from lunar regolith has been studied, but this work did not simulate the actual conditions that would be experienced in the lunar environment. Other beneficiation schemes have been proposed as concepts, but more research and laboratory experiments are needed.

Likely first candidates for Mars-derived propellants are CO and CH_4, if only because of the ubiquitous CO_2 atmosphere. The C and O components can be readily extracted using relatively simple processing methods. Hydrogen for the methane combination could be brought from Earth, or possibly recovered from martian permafrost in certain locations (directed surface exploration is required to confirm the resource utilization potential). Comparing these candidate propellants, simple expediency suggests choosing a bipropellant with a lower specific impulse as a good trade, in return for a smaller investment to install and maintain the surface chemical plant. This issue was addressed in performance assessments that follow.

The analysis of ISPP benefit to Mars missions proceeded in two phases. First, candidate ISPP propellants were applied to a single round-trip, assuming that the processing plant and all required support had been brought on line in previous missions, and ignoring continuing support requirements for propellant processing. This assessment of "steady-state" operational benefit of ISPP was used as a filter to identify promising propellant and process candidates, and to explore alternative implementation strategies for ISPP. The second phase of the assessment includes delivery of: the initial plant installation and supporting infrastructure (notably, the power source), continued maintenance and resupply of consumables or reagents, and end-of-life replacement of the hardware. Some of the key results of both phases of the assessment are summarized below.

Baseline Chemical Propulsion and Mars-only ISPP. With an Earth-derived all-propulsive approach, 1746 t must be delivered to LEO (Figure 1-2); this assumes that the entire Mars Transfer Vehicle (MTV) is returned to Earth orbit. Earth-to-LEO propulsion, shown as dashed lines in the figure, is not included in the mass statements. The reference mission design uses two techniques – a Mars aerobrake to reduce the capture



Mass Summary (t)					
LEO Mass from Earth	1746	666	861	895	976
Lunar Production	--	--	191	386	114
Mars Production					

FIGURE 1-2: Baseline Chemical and Mars ISPP

impulse and direct entry at Earth return of a 7 t Earth Crew Capture Vehicle (ECCV) -- to reduce the IMLEO requirement to 666 t. However, only the ECCV returns in this case; the rest of the MTV is expended.

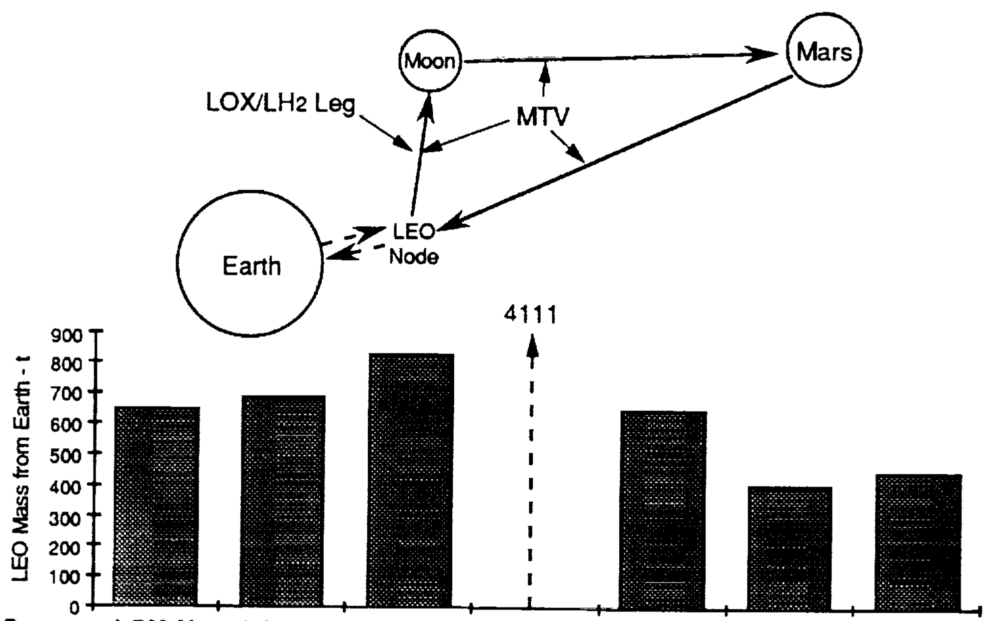
The three ISPP options shown in Figure 1-2 assume all-propulsive flight, with no aerobraking or ECCV direct entry on return. As with the all-propulsive baseline, all of these return the MTV to LEO where it could be refurbished for another flight. IMLEO masses for these three options are comparable, with Mars LOX/Earth LH_2 being heaviest, since the outbound leg carries hydrogen fuel for the return leg. However, the Mars production requirements differ substantially, depending on specific impulse of the particular bipropellant. The LOX/CH_4 case assumes that hydrogen is carried from Earth, and combined with carbon separated from the Mars atmosphere to produce methane.

The performance impact of carrying any propellant constituents on the outbound leg from Earth to Mars is indicated by the relatively small difference in IMLEO between LOX/CH_4, which requires hydrogen from Earth, and LOX/CO, which is formed entirely from Mars in situ resources. As compared to LOX/CH_4, LOX/CO gives up over 100 lbf-sec/lbm in specific impulse, and requires manufacture of twice as much propellant by mass. IMLEO for LOX/CO is only 34 t greater, since propellant for the Earth return is recovered 100% from Mars. However, including infrastructure requirements favors LOX/CH_4, as will be discussed on the following pages.

Although all three of the ISPP options require more IMLEO than using an aerobrake at Mars, it is important to note that the entire MTV is returned for possible reuse, whereas the Chem/Aero option returns the crew to Earth in an ECCV.

MTV 3-Leg Using LEO and Low Lunar Orbit (LLO). If lunar propellant is to be used for a Mars transfer, either the propellant can be brought from the Moon to a LEO transportation node, or the MTV can be fueled in low lunar orbit. Figure 1-3 shows the latter case as the requirements for mass in LEO delivered from Earth for several candidate propellant combinations. For example, a 647 t MTV would leave LEO for LLO, where it would take on 4346 t of LOX/Al propellant. Note that the 647 t includes an expendable LOX/LH_2 stage for the LEO-to-LLO leg.

Differences among the set of lunar LOX/metal propellants are readily apparent. LEO masses from Earth for LOX/Al and LOX/Si are comparable, with the higher LOX/Si requirement for tankage and structure to handle an additional 591 t of propellant. The LOX/Ti masses are higher because of the reduced specific impulse. Similarly, LOX/Fe, with Isp = 195 s, gives masses too large to be practical; LOX/Fe is eliminated from further consideration. LOX/Al-Mg performance is almost equal to LOX/Al; since LOX/Al-Mg will probably require two processing plants and shows no appreciable gain in performance, it is also eliminated.



LEO->Mars->LEO	LOX/Al	LOX/Si	LOX/Ti	LOX/Fe	LOX/Al-Mg	LOX/CH4 *	LOX/CO *
Mass Summary (t)							
LEO Mass from Earth	647	689	827	4111	650	404	448
Lunar Production	4346	4937	7230	58594	4399	460	906
Mars Production	--	--	--	--	--	210	425

* Both Lunar & Mars ISPP

FIGURE 1-3: MTV 3-Leg Using LEO and LLO

The last two bars on Figure 1-3 consider LOX/CH_4 and LOX/CO production at both the Moon for the outbound leg, and at Mars for the return leg. Both of these options show significant reductions in production requirements, since propellant for the return leg is not carried outbound. However, the lunar recovery requires extracting solar wind gases deposited in the regolith; this concept would require much more definition than exists now.

One frequently discussed alternative to the 3-leg scenario is to configure and fuel the MTV in LEO, using a lunar tanker to bring propellant manufactured on the Moon. This approach results in a much lower mass delivered from Earth for the MTV, but it also requires support for a complete round trip to the Moon to pick up a large propellant load. Including both the lunar and Mars round trips, total mass delivered from Earth would be higher than for the 3-leg scenario described above.

Infrastructure Assessment. A complete assessment of the requirements for utilizing lunar/Mars produced propellants for Mars missions must include the systems needed to manufacture propellant, sustain the manufacturing operation, and deliver these propellants from their point of origin to the point of application (Figure 1-4). In addition to these systems, maintaining the propellant plant operation will require continuous support. The effects of these requirements on the potential benefits offered by lunar/Mars propellant production can significantly offset the performance gains of using ISPP. The shaded items in Figure 1-4 are included in this assessment of infrastructure requirements - the second phase of our assessment of ISPP alternatives.

Figure 1-5 shows results for one such assessment, using lunar LOX with hydrogen from Earth for the Mars round trip. The Earth-delivered mass at "mission #0" (a place-holder for one or more flights, as required) includes the lunar propellant plant and specialized plant set-up hardware, lunar excursion vehicles to carry the plant down to the lunar surface from low-lunar orbit, and an expendable LOX/H_2 stage to transport these masses to LLO from LEO. The first Mars mission, mission #1, has a slightly higher Earth-delivered mass than steady-state requirements because it carries the MEV to Mars. In the steady-state mode, the Earth-delivered mass consists of the lunar plant support, Mars mission payload, MTV drop tanks, an aerodeceleration module for the MEV entry and descent phase, and the expendable stage to boost these payloads to LLO from LEO.

Using lunar LOX and hydrogen from Earth show a steady-state performance ratio of about 1.5, or a substantial reduction in mass for each mission. The lower graph in Figure 1-5 further shows a break-even

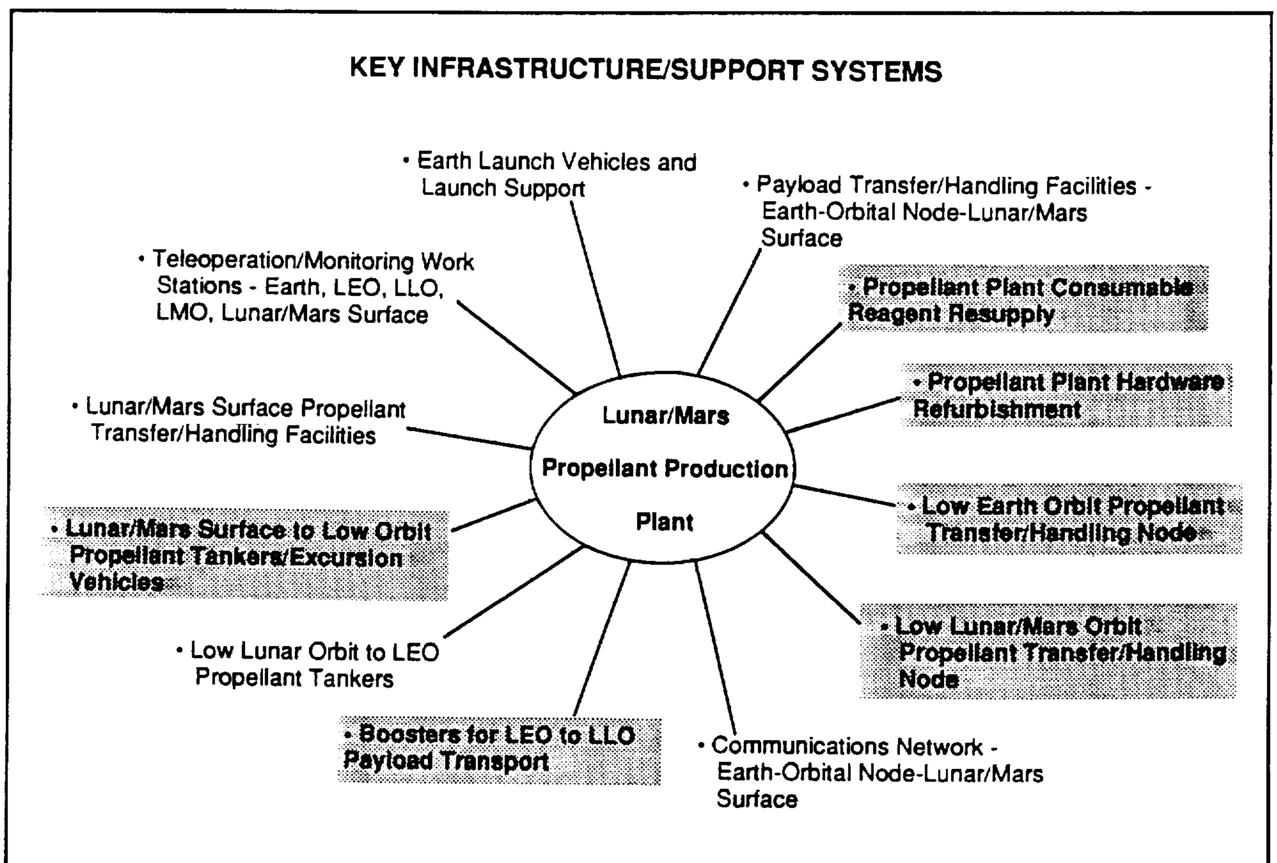


FIGURE 1-4: Key Infrastructure and Support Systems

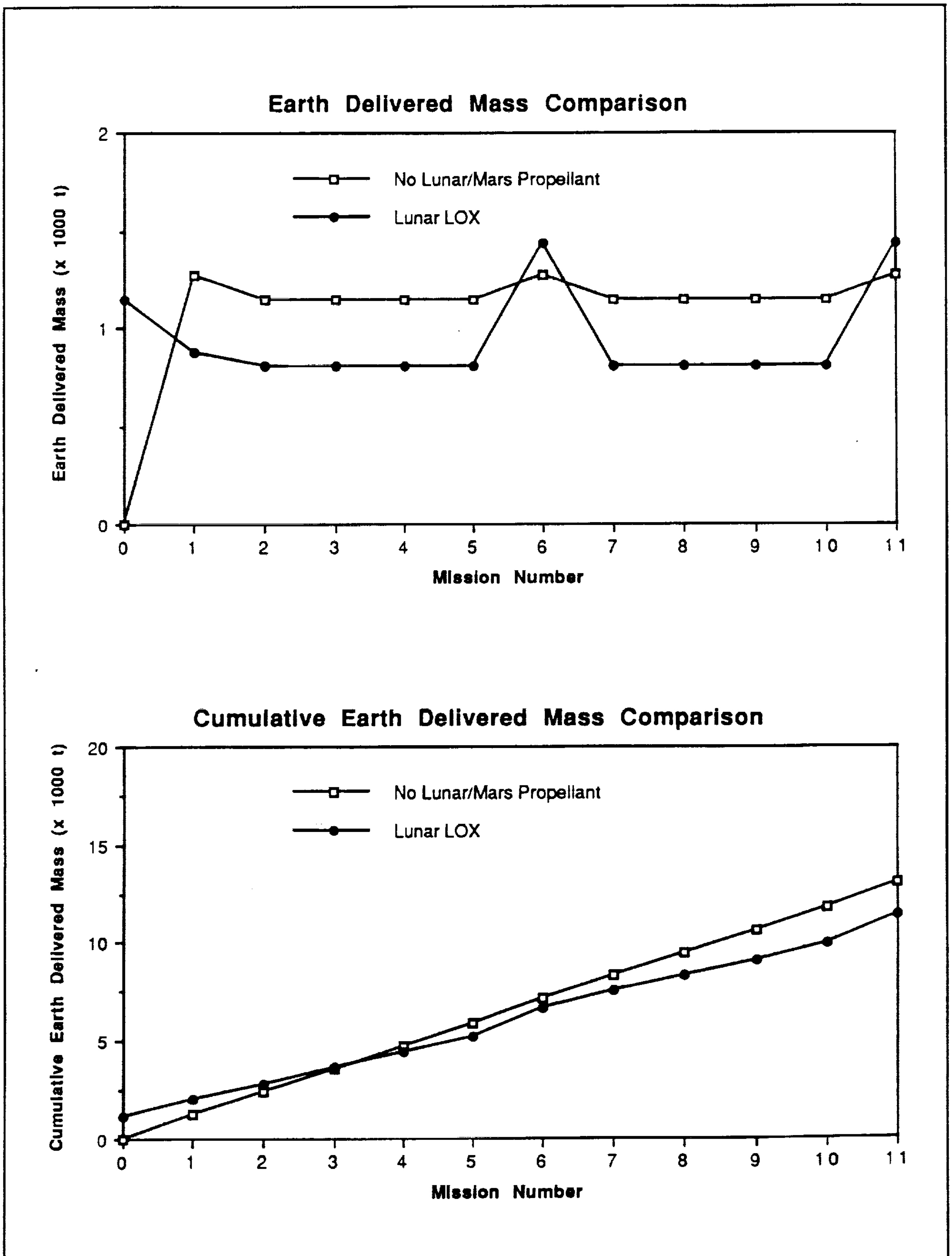


FIGURE 1-5: Lunar LOX with Earth LH

after three missions, including initial emplacement and continuing support requirements. Also, cumulative mass requirements over 11 flights (about two planned vehicle lifetimes) shows a savings of about 2000 t in total Earth-delivered mass.

Figure 1-6 shows the results for producing LOX/CH_4 at Mars. Mission #0 requirements are based on delivery of a LOX/CH_4 propellant plant using the MTV and MEV. The MEV is supplied with the propellant it needs to bring the plant down to the Mars surface. At mission #1, the propellant plant is operational and is producing propellant for the MEV and the MTV return trip. A new MTV and MEV are supplied for missions #5 and #10 when using Mars-produced propellant. This is one mission earlier than the previous case that does not use Mars-produced propellant, because the vehicles get their first use at mission #0 to deliver the propellant plant. Over 80% of plant support in this case is due to resupply of hydrogen for methane production. Note that the break-even point in total mass for this case is now at mission 4; the reason is that this case uses ISPP only for the return leg, whereas the lunar LOX in the previous case supplies the entire round trip.

The simplest processing scheme for producing Mars propellant would be the case where only Mars LOX is produced and hydrogen is supplied from Earth. This case, shown in Figure 1-7, has a relatively low Earth-delivered mass requirement for plant set-up, but does not provide a significant benefit for steady-state operation: ongoing hydrogen supply and plant refurbishment needs offset the lower setup cost. Only a small reduction in cumulative Earth-delivered mass is realized after 11 uses in Mars round trip missions -- probably not enough to justify the investment.

Lunar Outbound and Mars Return Propellant. For this scenario, lunar produced propellant is used to fuel the MTV for a LLO to Low Mars orbit (LMO) trip and Mars produced propellant is used to fuel the MTV for a return trip to LEO. An expendable stage is used to move the empty MTV, with tankage, lunar and Mars plant support, and the Mars mission payload from LEO to LLO where the cycle repeats. This scenario is shown schematically in Figure 1-8.

The results of this case are shown in Figure 1-9. This is the only case investigated with a reasonably low Earth-delivered mass requirement for set-up of propellant plants <u>and</u> a significantly lower Earth-delivered mass requirement in steady-state. The result is a mass payback after 3 missions and an Earth-delivered mass savings of almost 5000 t after 11 missions.

Since every case shows a value greater than one, just looking at steady-state results would indicate that any ISPP strategy is an improvement over the baseline. It is for this reason that many studies have suggested the use of various in situ propellants. The problem with only considering steady-state requirements is that

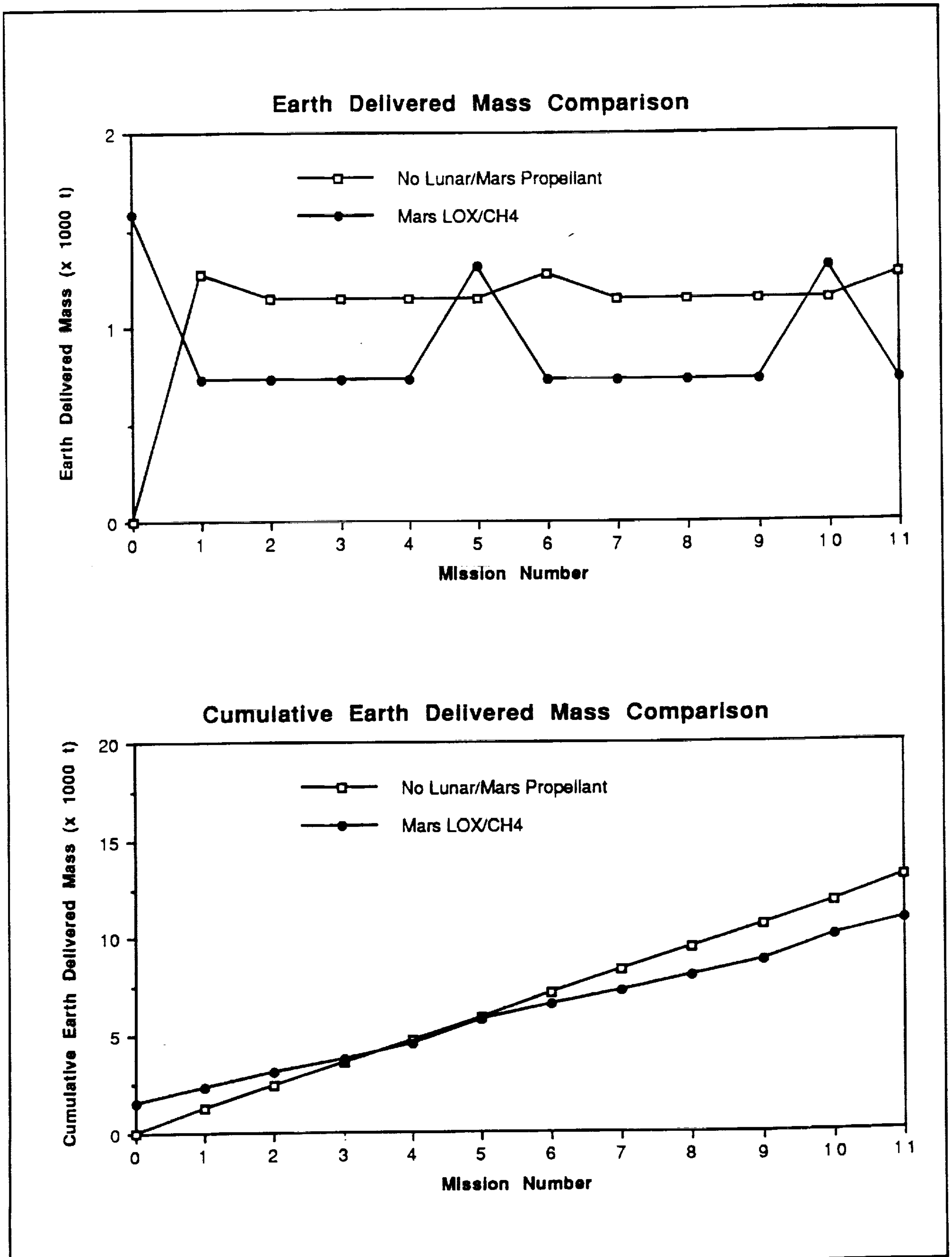


FIGURE 1-6: Mars LOX/CH_4

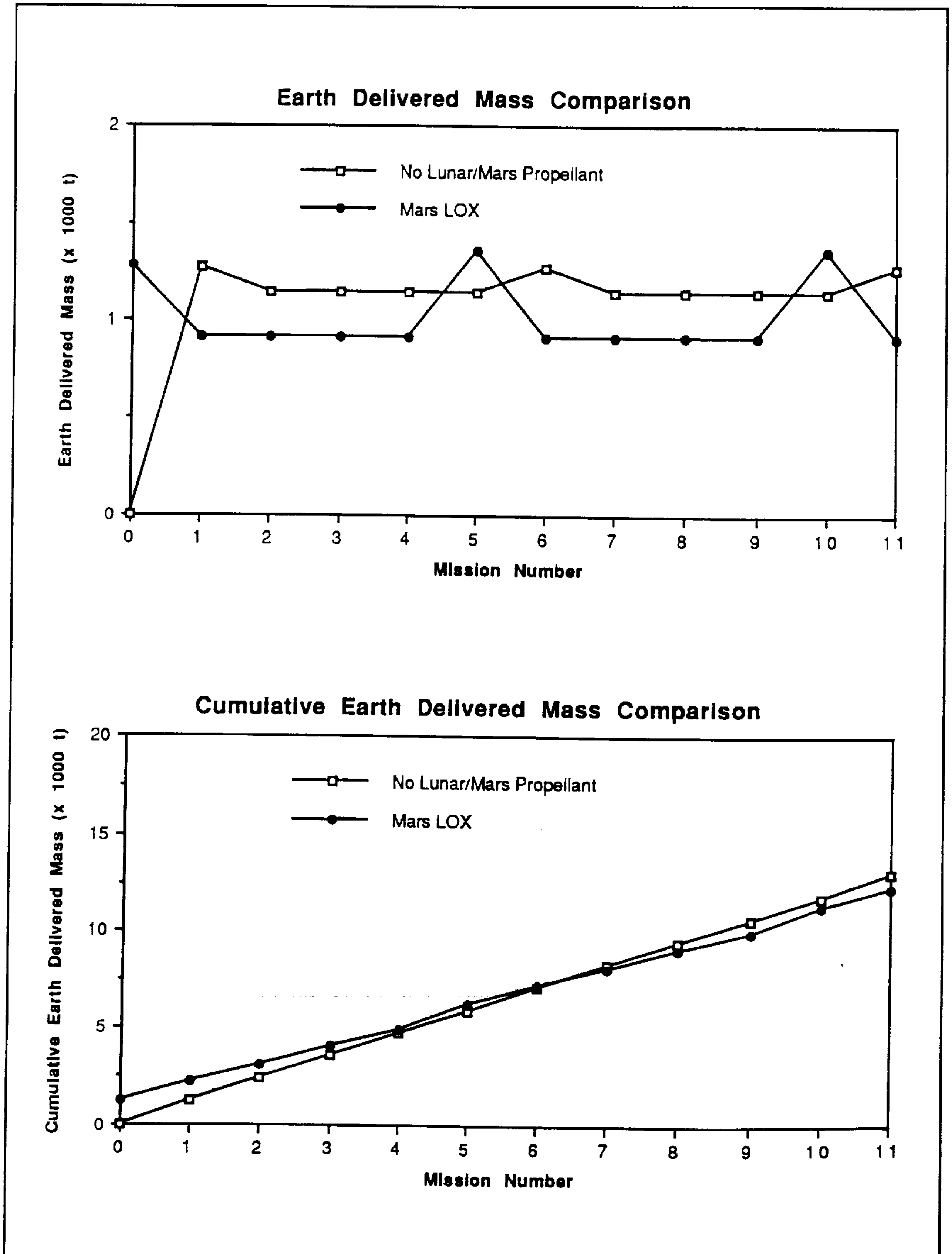


FIGURE 1-7: Mars LOX with Earth LH

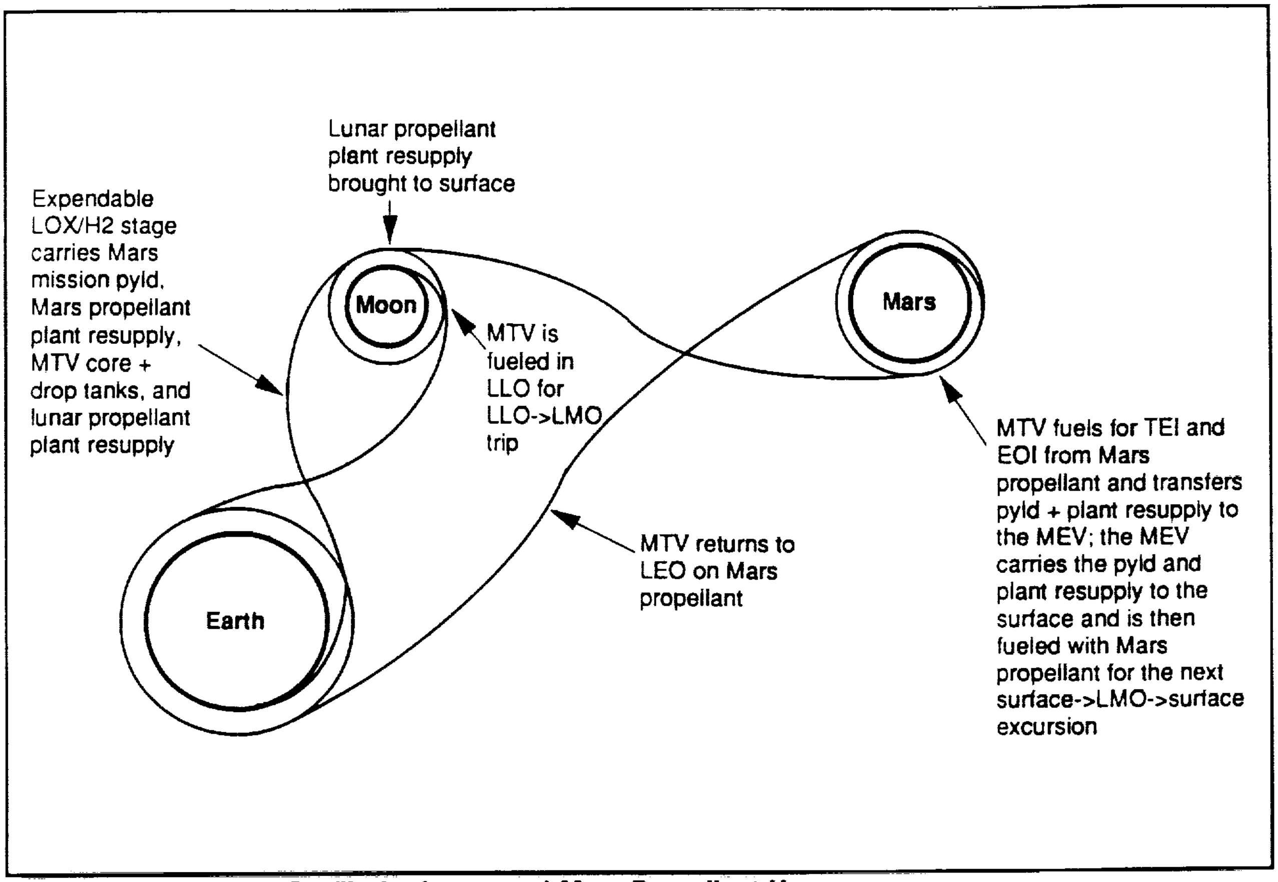
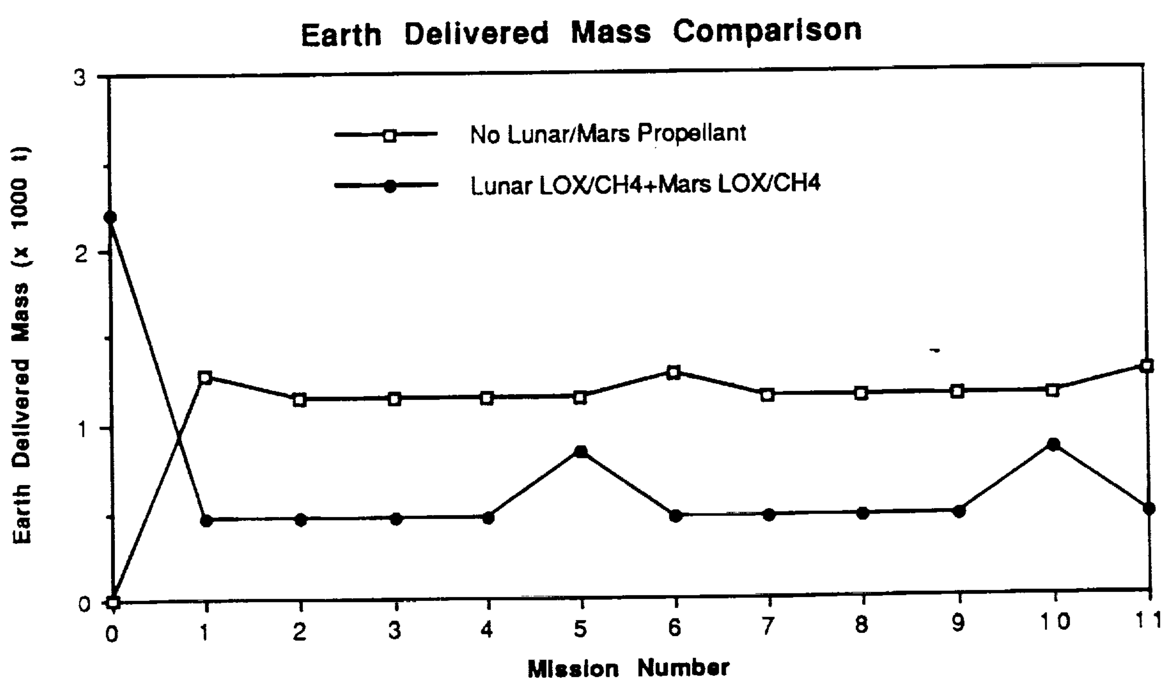


FIGURE 1-8: Mission Profile for Lunar and Mars Propellant Use

the effects of establishing the propellant production plants and resupplying new transfer and excursion vehicles is not taken into account. When the plant set-up and vehicle change-out requirements are considered, many of the cases that show a benefit for steady-state operation show only a minimal savings (or loss in the cases using lunar LOX/metal gels for the entire mission) in cumulative Earth-delivered mass, even when considering several Mars missions. The Earth-delivered mass savings (or losses) realized after 11 missions are summarized for all the cases in Figure 1-10. The two cases showing the greatest potential here are the lunar LOX with Earth-supplied hydrogen case and the case where both lunar and Mars LOX/CH_4 are used. The cases using lunar produced LOX/metal gels both required more than 4000 t additional Earth-delivered mass after 11 missions when compared to the case where no in situ propellant is used.

Sensitivity analysis (Section 6) of the different utilization strategies for the propellants considered in this study suggests that assessment results are most affected by the amount of consumed reagent that must be resupplied, plant hardware refurbishment assumptions, power required to drive processing and beneficiation (when needed), and the mass of the plant itself. Estimates for these requirements are preliminary in nearly every case. Most attention of researchers in this field has focused on the basic chemical processes, rather than on delivery, installation, operation, and maintenance.

A key finding of this study is that the best use of lunar and martian resources for propellant manufacture is not yet clear. To make intelligent choices of which propellant(s) to use and which processes best recover them, mission planners will require better understanding of many issues that impact "life cycle" comparisons between candidates: plant design, lunar beneficiation requirements, realistic operations scenarios including process duty cycles and crew support, storage and handling of intermediate and final products, consumables resupply, and requirements for maintenance and refurbishment. Many alternatives have been identified, but none stands out as clearly best.



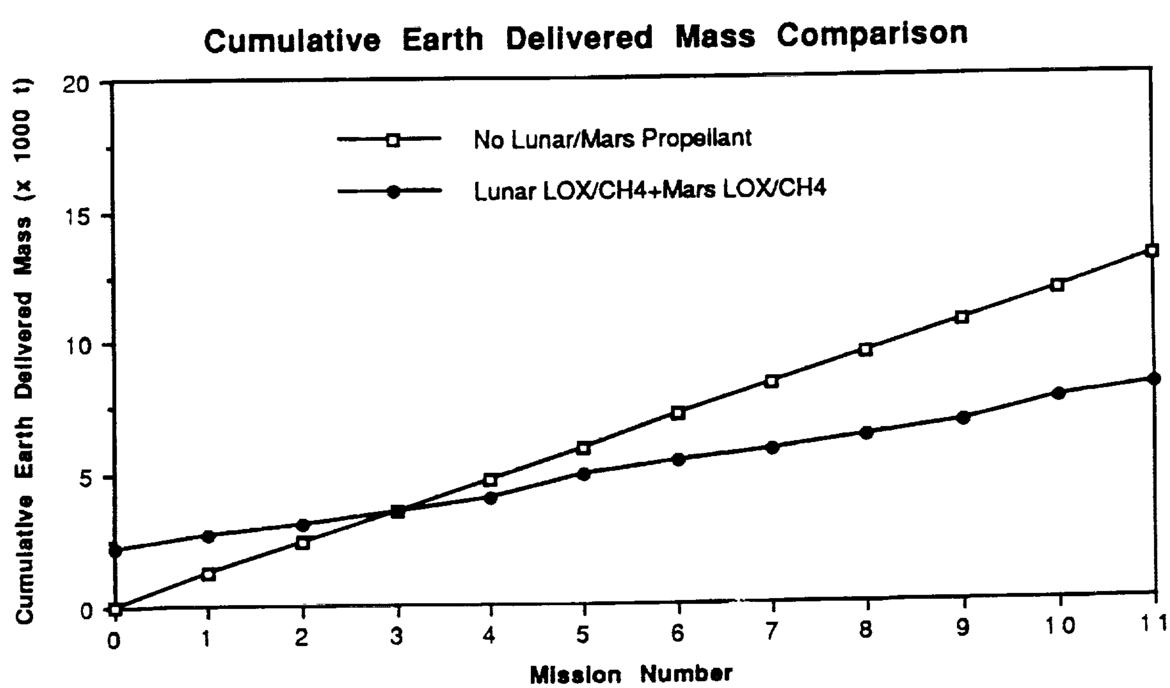


FIGURE 1-9: Lunar LOX/CH_4 and Mars LOX/CH_4

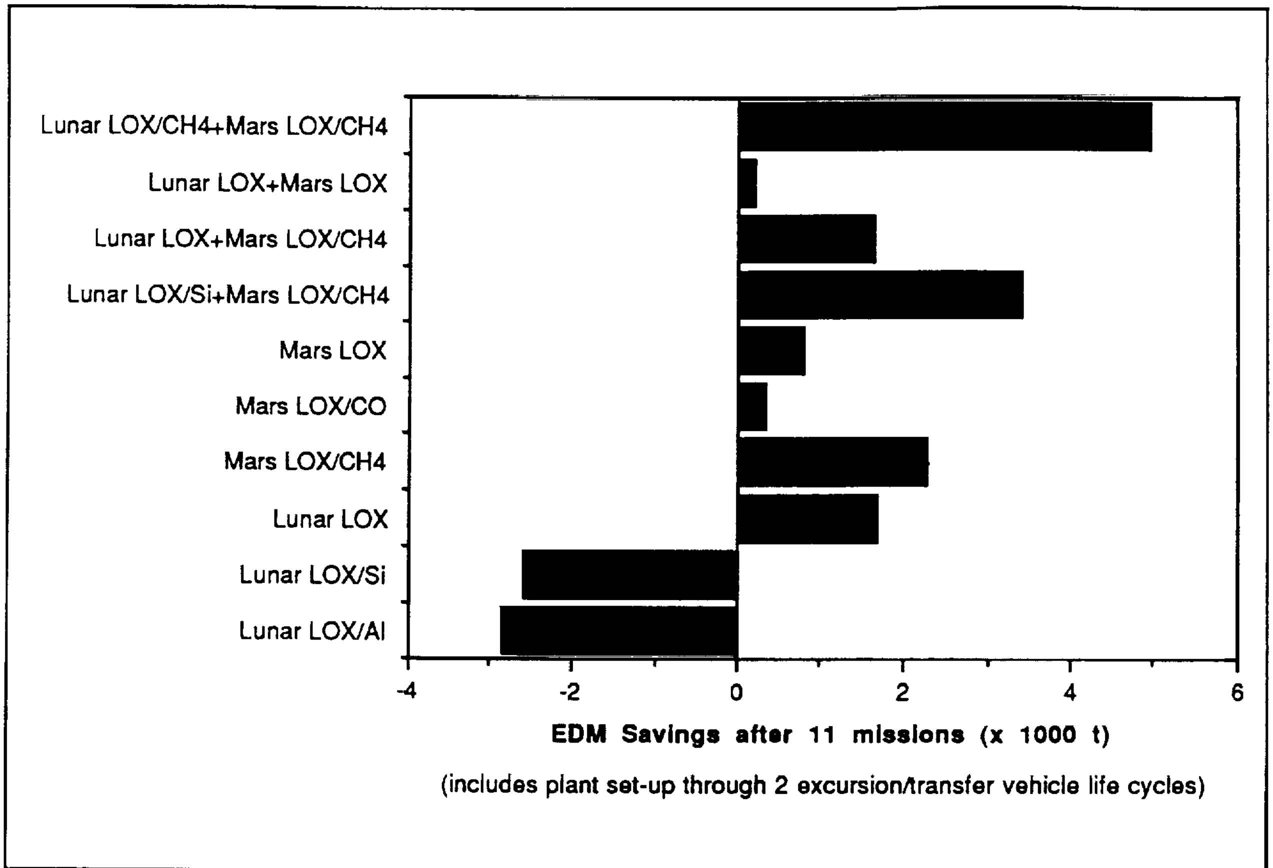


FIGURE 1-10: Earth-Delivered Payload Savings

2. INTRODUCTION

The reference propulsion system for lunar and Mars exploration is an advanced design that burns liquid oxygen/liquid hydrogen (LOX/LH) bipropellant at a higher specific impulse than the current version of the RL-10 engine. However, improved engine performance using chemical bipropellants is not, by itself, sufficient to capture the missions as currently planned, given expected launch vehicle constraints, flight rates, etc. Using propellants brought from Earth, the baseline space transportation system also requires the use of aerobraking techniques to reduce capture impulses (Report of the 90-Day Study 1989). LOX/LH is the high-performance chemical bipropellant for all applications (transfer, descent, ascent, circularization burns, and mid-course adjustments); current plans anticipate development of a single advanced chemical engine that would serve main propulsion needs for all vehicles and uses. Later, LOX produced on the Moon from local resources would be combined with hydrogen fuel from Earth for use in the Lunar Excursion Vehicle (LEV) ascent and descent. LOX supplies could also be used for the Lunar and Mars Transfer Vehicles (LTV and MTV, respectively). The potential leverage of this in situ propellant production (ISPP) approach is limited by continued reliance on the need to bring adequate hydrogen supplies from Earth.

2.1 OBJECTIVE

The objective of this study was to analyze the potential application for SEI missions of propellants made exclusively from lunar or martian resources. We focused on application of the candidate propellants to piloted Mars missions. Using such propellants could minimize or eliminate the cost of carrying propellant for subsequent powered maneuvers by the excursion vehicles and return transfers through Earth's gravity well and the large Earth departure impulse. Certain chemical mono- and bipropellants are candidates for this approach; they could be recovered entirely from in situ resources on the Moon and Mars, without requiring a significant, continuing Earth-based resupply of propellant constituents (e.g., fuel to mix with a locally obtained oxidizer), and with minimal need to resupply consumables (e.g., reagents or catalyst for process reactions).

2.2 SCOPE OF STUDY

Since the propellant supply is clearly the largest component, by mass and volume, of any Earth launch or LEO departure configuration, any means of reducing the amount of propellant needed is of potential interest to mission planners. One attractive possibility is to refuel along the way, eliminating the need to bring the entire propellant supply from Earth. Various implementations of this approach have been proposed and studied as lander missions have improved knowledge of lunar and martian raw material abundances. If all the propellant constituents were available locally, Earth supply requirements might be minimized.

This point leads us to consider metallized monopropellants as candidates for lunar processing. Both oxygen and several candidate metals have been shown to be available in lunar rocks and regolith. Monopropellants would have a substantially lower specific impulse than metallized bipropellants, but there would be no need to transport hydrogen fuel from Earth, or to recover it on the Moon. Section 3 will examine this tradeoff in detail for five monopropellants that could be made using only lunar resources:

LOX/Al
LOX/Al-Mg
LOX/Si
LOX/Ti
LOX/Fe

Several processes have been suggested for recovering oxygen from various lunar minerals, or from bulk processing of whole regolith. Many of these processes can also serve as the basis for recovering the metals of interest; these will be examined in some detail.

Although the recovery process presents some major engineering problems, the prospect of recovering volatiles on the Moon is interesting for several reasons. First, hydrogen and carbon, deposited by the solar wind on the Moon's exposed surface, could be used for high-performance chemical propulsion. Second, ability to recover LOX/H_2 or LOX/CH_4 from lunar resources would mean a second source for well-known bipropellants, without the expense of bringing the full load from Earth. Finally, Mars atmospheric resources, and the possible existence of water on the surface, suggest that the same propellant could be manufactured at both the Moon and Mars, maximizing effective use of the gas station approach to vehicle fueling. We considered two bipropellants that could be made from lunar regolith or the Mars atmosphere: LOX/CO and LOX/CH_4. To manufacture methane on Mars, we assume that hydrogen supplies are brought from Earth. Although there is strong evidence for water deposits on the Mars surface, what is known of probable locations imposes severe constraints on landing site selection, and adds substantial penalties to excursion vehicle propulsion requirements. Therefore, producing LOX/CH_4 (or LOX/LH) exclusively from martian resources has not been examined in this study.

Each candidate propellant was evaluated in several ways. First, lunar raw materials that would be required were reviewed for locations and abundances, using the results of many workers analyses of lunar samples and surface characterizations. Since several alternatives suggested for lunar processing require different feedstocks for operation, the characterization of lunar regolith is treated generically, to support evaluation of all of these. Second, the recovery and manufacturing steps for each process are described and characterized with respect to several criteria:

- feedstock volume
- rate of reaction
- estimated peak power and total energy to drive the process
- output (or throughput) rate

- plant duty cycle
- handling and storage facilities
- plant mass and volumetric requirements
- mass and volume of surface processing support infrastructure elements

Surface infrastructure elements, such as power supplies, are shared resources that would be used by many "customers." To avoid an unfairly conservative assessment of propellant production, these resources have been included at a pro rata value where required.

Each candidate propellant was evaluated for a single piloted Mars round trip, assuming that the production plant(s) and all necessary supporting infrastructure have been delivered and brought on-line on previous missions. The purpose of this step is to examine the "steady-state" performance potential of the candidates, compare them to each other, and compare them to baseline LOX/LH produced on Earth. The in situ propellants were first evaluated in the reference mission scenario, assuming that the Earth-Mars staging point for departure and return is LEO. Then, variations on the mission profile were examined to take advantage of changes made possible by in situ production.

The study also included comparative evaluation of performance potential combined with plant delivery and ongoing operational resupply needs, support, and infrastructure requirements. This analysis is required to fully assess the feasibility of any candidate; examining only steady-state performance potential ignores many issues that could impact a planning decision to include or exclude ISPP.

2.3 APPROACH

Figure 2-1 gives an overview of the approach used to perform this study. Each candidate propellant was assessed from three different, although not necessarily independent, perspectives: processing requirements, single-mission performance analysis for the MTV, and multi-mission performance with infrastructure requirements included. The intent of this approach was to survey the candidates (propellants, processing options, and mission profiles), and to select for further evaluation only those alternatives most likely to benefit the SEI program. These would be subjected to a detailed assessment of infrastructure requirements, multi-mission performance potential, and impacts on the overall architecture of lunar and Mars exploration. As the following sections will describe, the preliminary results did not warrant eliminating very many options; this is especially true of the processing options.

The resource survey of lunar materials was based on a brief statistical analysis of the reported results of mineral, oxide, and elemental composition of the Apollo and Luna samples. Relative abundances for each oxide and element of interest were computed by site for the lunar regolith. Processing options are described, and their support, operation, and refurbishment requirements are identified. Each process's output potential is computed; for those that produce oxygen and one or more metals, output is normalized to a specified quantity of oxygen produced.

Mass delivered to LEO from Earth is the figure of merit used for performance evaluation. The Mars round-trip profile is taken from the reference 90 day study result, together with assumptions on delivered payloads, vehicle masses, and related assumptions (Priest and Woodcock 1990). Some additional assumptions concerning the infrastructure and support requirements were made for certain processes, as indicated in sections 3 and 4.

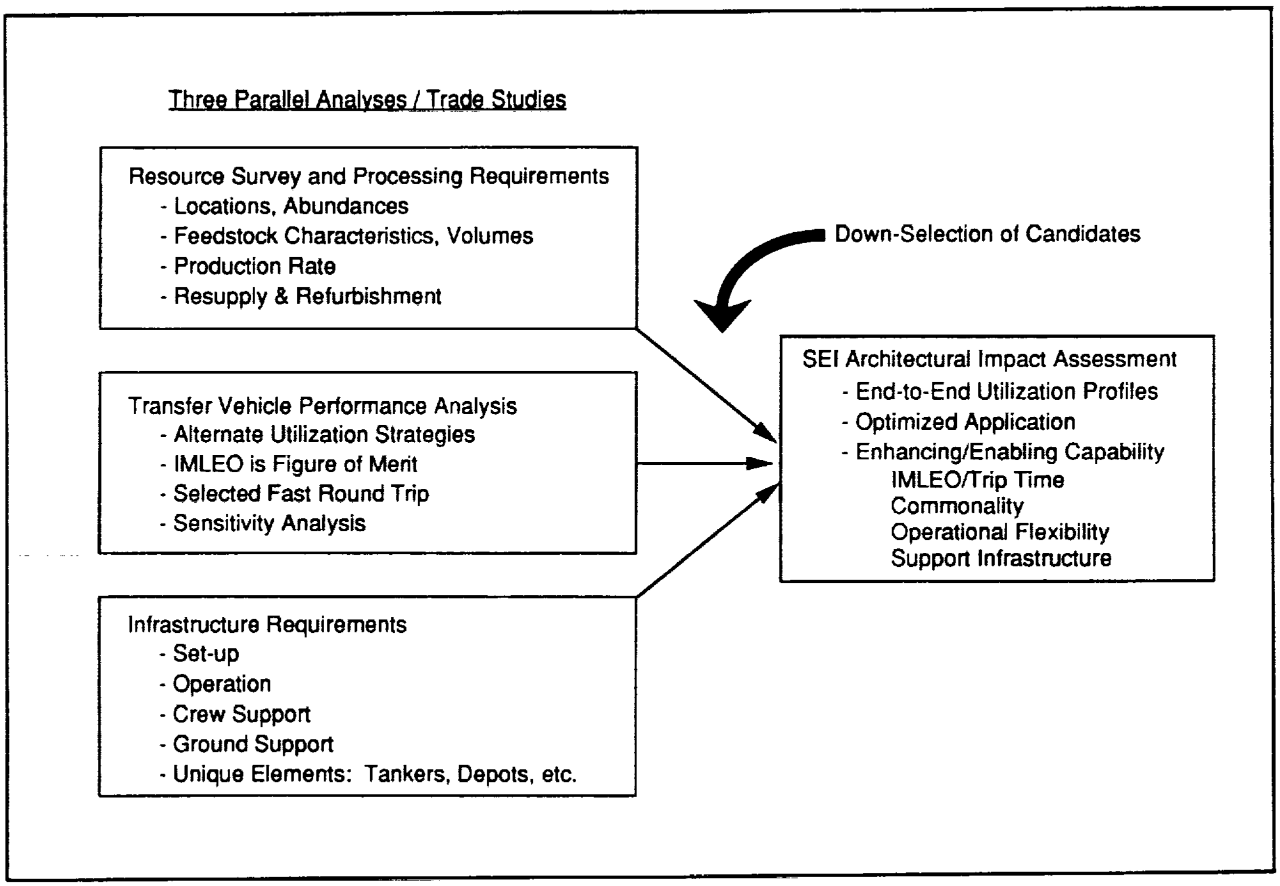


FIGURE 2-1: Study Approach

3. CANDIDATE PROPELLANTS FROM LUNAR REGOLITH

Past studies by SAIC and others suggest that using in situ produced propellants is most advantageous near their point of manufacture. If the supply line is too long, the shipping costs become prohibitive. The probable first, best use of any propellant produced on the Moon will be in lunar transportation elements: ascent and descent of the LEV, perhaps followed by use in the LTV return to Earth orbit. With the appropriate implementation strategy, lunar propellants may also show an advantage for trans-Mars propulsion needs. This section reviews the available lunar raw materials and the chemical processes for making metallized monopropellants on the Moon. Process support requirements, such as beneficiation of feedstock and power, are discussed. We also review more speculative options for recovering volatile elements deposited in lunar regolith by the solar wind.

3.1 LUNAR IN SITU RESOURCES

Many alternative raw material feedstocks have been proposed for propellant manufacture from in situ resources at the Moon. The selection of an alternative would be determined by several factors: final mission requirements, performance impact of the resulting propellant, and feasibility of in situ processing. Whether a candidate process is feasible will be determined, in part, by the availability of the raw materials required to feed the process. The first step in our assessment of the candidate lunar propellants was a survey of known data on the abundances and distributions of possible feedstocks.

The Moon's surface was formed by volcanic activity, followed by meteorite bombardment, forming cratered highlands and mare regions (or "seas"). The entire surface is covered by a layer of regolith -- fine-grained rock fragments and lunar soil – that formed as the result of continual micrometeorite impacts. The highlands comprise about 85% of the Moon's surface area, and generally contain higher concentrations of lighter elements, such as aluminum and silicon, that solidified from the magma ocean. Regolith covers the highlands to several meters depth in most locations, up to a maximum of about 10 m. The maria cover the remaining 15% of the global surface area, but are concentrated on the near side, comprising about 30% of its surface. Heavier, denser materials are concentrated here, including the iron, magnesium, and titanium of interest in this study.

What is known of the elemental and mineralogical composition of the lunar surface is based primarily upon analyses of portions of the 383 kg of samples returned by nine Apollo and Luna flights. The landing sites (Table 3-1) included the lunar mare, hilly uplands and highlands regions, and transition zones. The Apollo and Luna sample return missions covered an area of the lunar near side extending from 27 degrees north to 9 degrees south latitude, and 23 degrees west to 62 degrees east longitude.

TABLE 3-1
LUNAR SAMPLE SITES

Mission	Landing Site Coord.	Landing Site Map Name	Site Description	Total Samples
Apollo 11	0.7N 23.4E	Mare Tranquilitatus	SW part of mare, 50 km from nearest highland	21.9 kg
Apollo 12	3.2S 23.4N	Oceanus Procellarum	NW rim of 200m dia crater	33.9 kg
Apollo 14	3.7S 17.5W	Fra Mauro Highlands	Broad, shallow valley between radial ridges of Fra Mauro formation	43.5 kg
Apollo 15	26.1N 3.7E	Palus Patredinis	Mare plain at eastern margin of Imbrium Basin	77.1 kg
Apollo 16	9.0S 15.5E	Descartes Highlands	Two morphologically distinct units at landing site: highlands plains-forming unit (the Cayley Formation); ridges and mts of the Descartes Highlands	96.6 kg
Apollo 17	20.2N 30.8E	Taurus-Littrow	SE rim of Mare Serenitatis in a dark valley deposit	110.2 kg
Luna 16	0.7S 56.3E	Mare Fecunditatus	NE part of mare; no radial systems of large craters in this area	0.11 kg
Luna 20	3.5N 56.5E	Crisium Basin Rim	Highlands region between two maria	0.05 kg
Luna 24	12.7N 62.6E	Mare Crisium	SE part of mare approx 18 km SE of Fahrenheit crater	0.17 kg

This small suite of samples, taken from a limited number of surface locations, is much less than a complete characterization of the lunar mineral locations and abundances. Most samples collected on Apollo and Luna missions were taken from surface deposits and included regolith, rocks, breccias, and agglutinates. Some core samples of the regolith were also taken, the deepest penetrating to approximately 3 m. The regolith, exposed to continual bombardment by micrometeorites, is representative of the chemistry and mineralogy of the underlying bedrock. However, the rock fragments, breccias, and agglutinates (major constituents of the surface material) may have been transported to their collection sites as a result of impact or explosive volcanic events. Rocks transported in this manner usually become chemically contaminated and physically altered and do not necessarily represent the parent rock. Therefore, the Apollo and Luna collections do not represent pristine samples of either mare basaltic rocks or highland crustal material (Dasch et al. 1989, and Vaniman et al. 1984).

Measurements of the Moon's surface elemental composition were made using the gamma-ray spectrometer and x-ray fluorescence experiments aboard the Apollo 15 and 16 command modules while in lunar orbit.

These measurements covered narrow swaths about the lunar equator (Apollo 16), and a strip inclined 29 degrees to the equator (Apollo 15). Combined analysis of collected samples and orbital data produces a characterization of the distributions and abundances of Al, Si, Fe, and Ti on the lunar surface.

Apollo and Luna regolith samples were analyzed to determine the distribution and relative abundances of SiO_2, TiO_2, Al_2O_3, FeO, and MgO at each sample site. For each site, an average oxide percent by weight was calculated from reported values for specific samples (as documented in Appendix A). A similar calculation was made for elemental abundances. The results of this analysis are summarized in Table 3-2. Figures 3-1 and 3-2 illustrate the average oxide abundances at maria and highlands sites.

TABLE 3-2
LUNAR REGOLITH COMPOSITION

Oxide or	APOLLO SITES						LUNA SITES		
Element	A11	A12	A14	A15	A16	A17	L16	L20	L24
	Lunar Oxides: Average Percent (by Weight) of Samples								
SiO_2	41.9	46.5	47.9	46.0	45.1	41.7	42.2	42.8	45.4
TiO_2	7.4	2.6	1.8	1.6	0.6	6.7	3.3	0.5	1.1
Al_2O_3	14.1	13.4	18.1	13.9	27.3	14.3	15.8	23.6	11.1
FeO	15.7	16.3	10.6	15.1	5.3	14.5	17.1	6.6	20.5
MgO	7.9	9.8	9.5	10.9	5.7	9.9	8.8	9.5	10.2
CaO	11.9	11.0	11.1	10.7	15.7	11.5	12.8	14.4	11.0
other	1.0	<1.0	<1.0	1.8	<0.5	1.4	–	2.6	<1.0
	Major Element Composition: Average Percent (by Weight) of Samples								
Si	19.7	18.8	22.5	21.6	21.1	18.6	20.5	21.0	20.0
Ti	4.5	2.1	1.1	1.3	0.3	5.7	2.1	0.3	0.7
Al	7.3	7.2	9.3	5.5	14.4	5.8	8.2	12.2	6.6
Fe	12.3	14.8	8.0	15.4	4.0	13.6	12.8	5.7	14.6
Mg	4.8	6.6	5.9	6.8	3.5	5.8	5.3	5.6	5.7
Ca	8.6	7.5	7.4	6.9	11.3	7.6	8.6	10.1	8.1
O	42.8	42.3	45.8	41.3	44.6	39.7	41.6	44.6	N/A

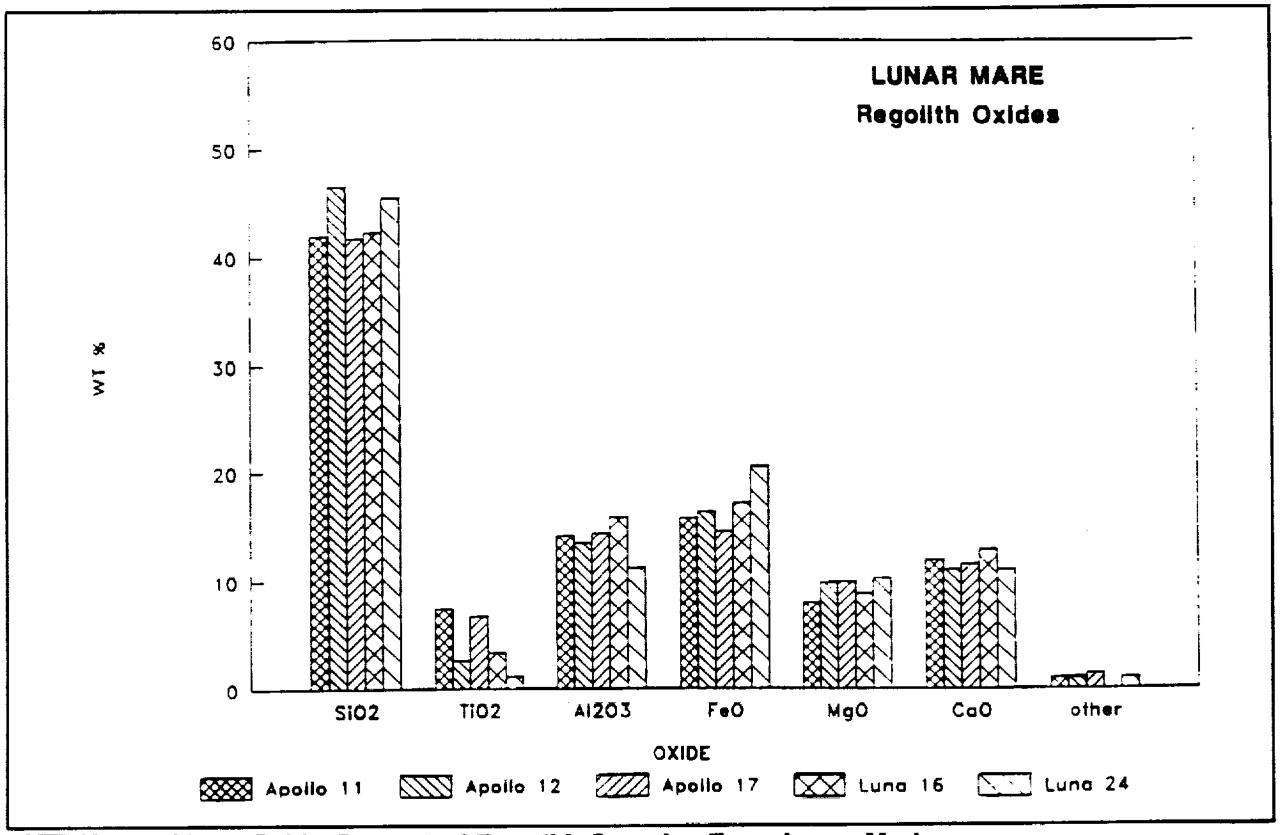


FIGURE 3-1: Metal Oxide Content of Regolith Samples From Lunar Maria

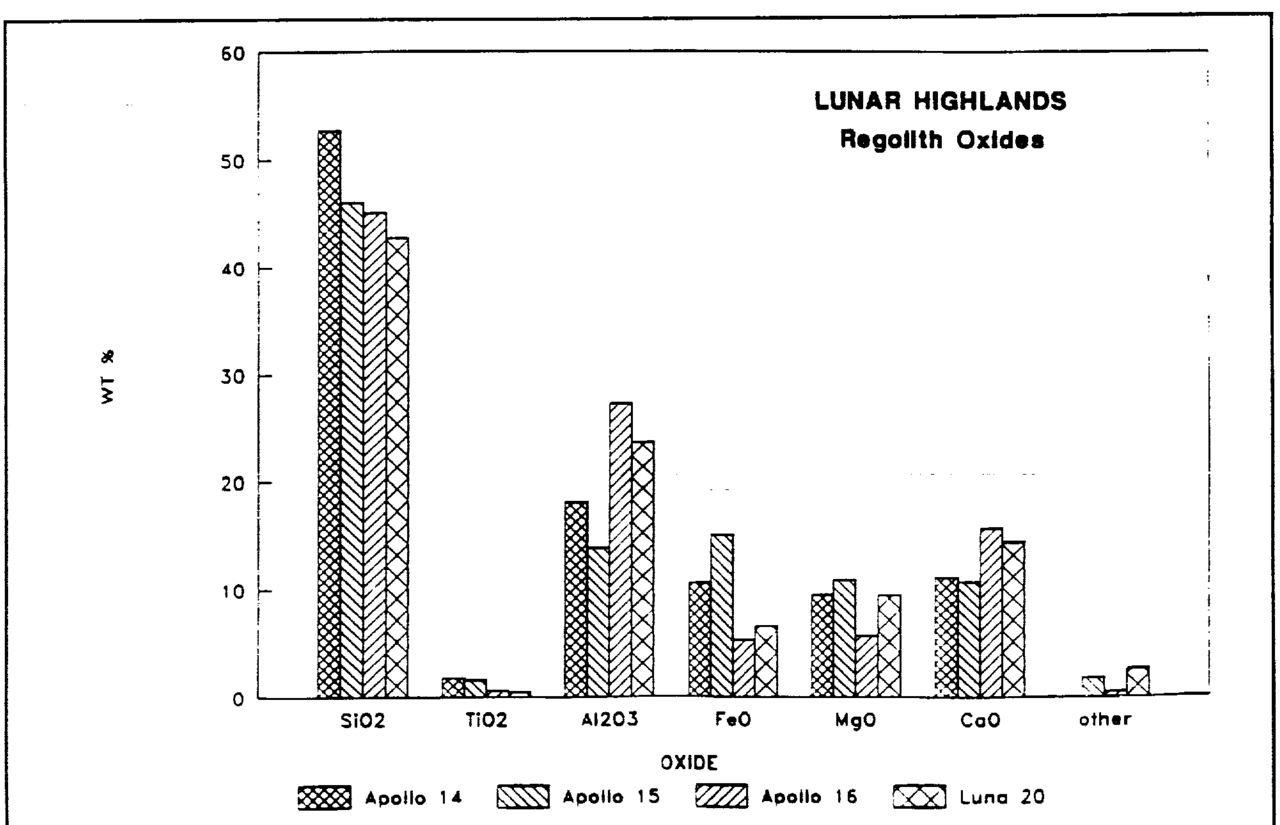


FIGURE 3-2: Metal Oxide Content of Regolith Samples From Lunar Highlands

The silicate and magnesium content of the lunar surface is relatively constant with SiO_2 comprising, on average, 40-50% by weight, and MgO averaging about 10%. Or, in terms of elemental composition, Si and Mg abundances average roughly 20% and 5%, respectively. Note the uniformly high percentage of silicon dioxide present at all sites.

The greatest variability occurs in the relative concentrations of Ti, Fe, Al, and their oxides. At 4.5-5.7%, the Apollo 11 and 17 sample sites show the highest titanium content while the maria sampled by Apollo 12, Luna 16, and Luna 24 are characterized by a low titanium content of no more than 2.1%. Iron content of maria material ranges from 12.3-14.8% as compared to 4.0-15.4% in the highlands. The highest aluminum content occurs at the Apollo 14 and 16 sites and Luna 20 site, where highland material was sampled. In these regions, the range of Al concentration is 9.3-14.4% for sampled material as compared to only 5.5-8.2% in the maria samples.

Although our review of reported sample values indicates reasonably good correspondence between regolith and basaltic rock sample averages for each site, the regolith values need not correspond with local rock geochemistry. Regolith samples from maria could include material transported from nearby highlands, and vice versa, by meteorite impacts or volcanic processes. This point would be of significance for any chemical process that requires a concentrated ore deposit feedstock for economic viability.

The major metal elements of interest for use in propellants -- Si, Ti, Al, Mg, and Fe -- are available in the following general mineral forms in regolith:

Ilmenite	$FeTiO_3$
Olivine	$(Mg,Fe)_2SiO_4$
Plagioclase	$(Na,Ca)Al(Si,Al)Si_2O_8$
Pyroxene	$(A,B)Si_2O_6$

For pyroxene, A and B are placeholders for any of several possible metal constituents. The primary source of Al is the mineral anorthite (a plagioclase mineral and the major rock-forming mineral of the igneous rock, anorthosite). The pyroxenes (two forms in particular - diopside and hypersthene) and olivines are sources of Mg and Fe. Ilmenite is a major source of Ti and Fe. Figure 3-3 represents the whole rock mineralogy of the rocks collected at the Apollo 11, 12, 15, and 17 sites. The highest concentration of anorthite (40 to 70% by weight) is located in the highlands (represented by Apollo 15 and Apollo 17 samples from nearby mountains and massifs). The highest ilmenite concentrations (over 20%) occur in the mare regions sampled by Apollos 11 and 17; the lowest concentration is in the highlands sites (<2%). All of these minerals (except ilmenite) are silicates, the primary constituent of the lunar crust.

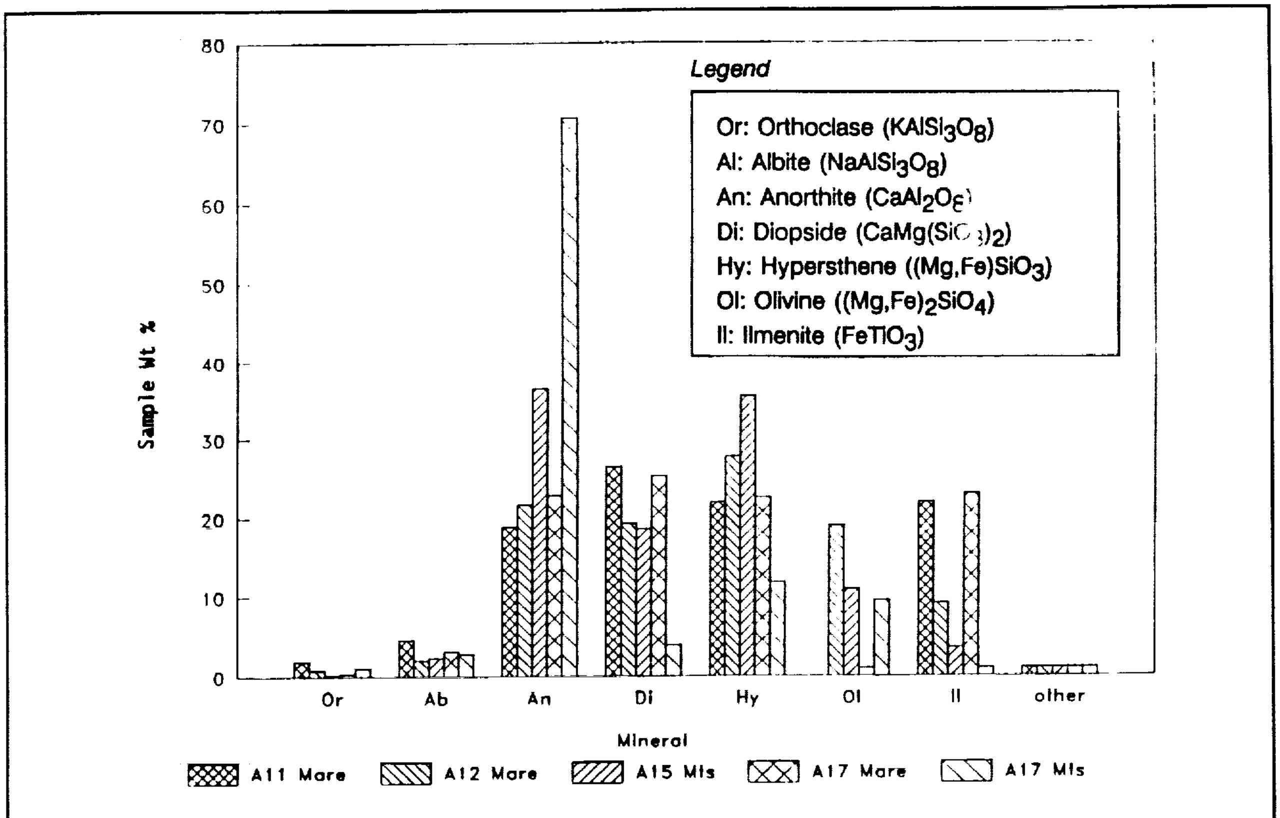


FIGURE 3-3: Whole Rock Mineralogy of Samples from Apollos 11, 12, 15, and 17

Volatile gases deposited by the solar wind are also possible lunar resources for propellant production. The Moon's surface is exposed to continual bombardment by the solar wind. The composition of the solar wind includes molecules of various gases: H, He, N, C, O, Na, P, S, the noble gases Ne, Ar, Kr, and Xe, and others that are present in trace amounts. As a result, the lunar regolith has collected volatiles in the form of molecules or atoms that are weakly bound to the surfaces of regolith grains (Cooper 1990). Aside from scientific interest in this repository, these volatiles might be useful as manufacturing resources. The first issue is whether their concentrations are high enough to make recovery economical.

A statistical analysis of the gas concentrations of H, He, N, and C was conducted by Bustin & Gibson (1991) and Phinney et al. (1977) to estimate their distribution by sample location. The soil samples used in this analysis represent bulk lunar soil only. Figure 3-4 illustrates the gas concentration distribution from sites sampled by the Apollo and Luna missions. At each sample site, C is the most abundant volatile (95-135 ppm) followed by N (60-119 ppm), H (45-80 ppm), and finally He (8-60 ppm). The exception to this apparent trend is the regolith of Mare Tranquilitatus where He, at 60 ppm, has a higher concentration than H at 51 ppm. Of the Luna sites, Mare Fecunditatus has the highest N concentration (134 ppm). The Crisium Basin rim yields N concentrations of 107 ppm. No data were available for H, He, and C from these sites.

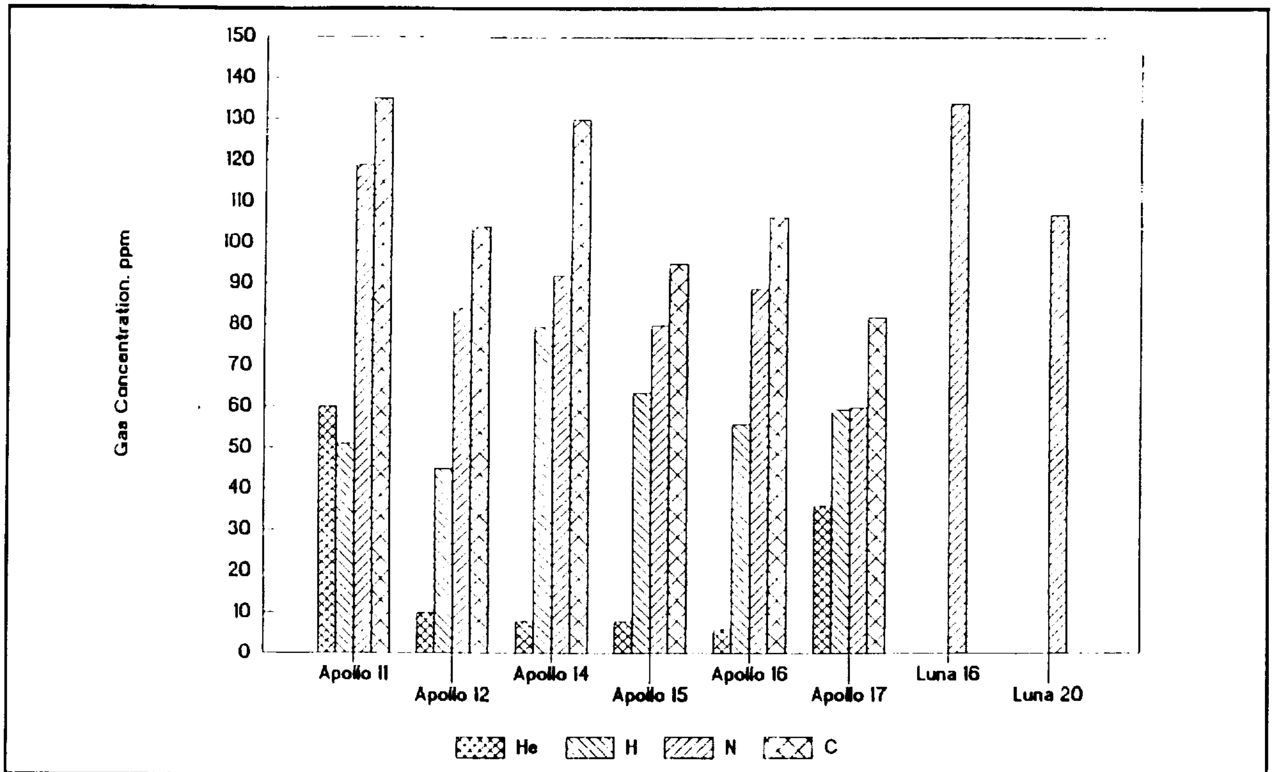


FIGURE 3-4: Solar Wind Volatiles Concentrations from Apollo and Luna Samples

This analysis is only a brief examination of the availability of useful volatiles in the lunar soil; further investigation would be required to fully assess the potential of solar wind gases as an exploitable resource at the Moon. For example, a characterization of the volatiles bound into specific minerals such as ilmenite would help to determine raw material feedstock needs for recovery processing. A processing concept that would recover carbon monoxide or methane fuel from solar wind deposits is discussed in the next section.

3.2 LUNAR MATERIAL RECOVERY AND PROCESSING

Many candidate processing schemes have been studied for propellant manufacture on the lunar surface. The emphasis of this work has been on recovering oxygen to be used in a chemical bipropellant with fuel supplied from Earth. Some of these studies have examined extraction of additional lunar resources, often with emphasis on elements, such as aluminum and iron, that could be useful in lunar construction; but the main focus of system concept designs was acquisition of oxygen. Several candidate processing concepts are reviewed and assessed in this section; they are divided into two broad groups: processes based on terrestrial counterparts, and space-based processes.

Terrestrial mining and resource extraction methods use readily available resources to expedite processing or reduce cost; on Earth, the abundant supplies of oxygen, hydrogen, carbon, and water are used extensively. Because these resources are not readily available on the Moon, lunar processes derived from terrestrial experience must be modified to conserve these and any other reagents delivered from Earth.

Other methods have been proposed that do not require reagents, but make use of thermal or electrical energy to separate various constituents of lunar regolith. These processes could be considered "space-based": they are not the most economical choices for processing on Earth, but they may offer advantages in space, where energy is more readily available than reagents. Experience with these processing candidates is very limited, and materials technology advances are likely to be required even to test these processes in a relevant environment.

Alternative Approaches

Thirteen lunar-based processing candidates (Table 3-3) were selected for detailed consideration in this study.

TABLE 3-3
CANDIDATE LUNAR PROPELLANT PROCESSES

Process	Resources Recovered	Potential Amounts Obtained per 100 t O2
Processes based on terrestrial counterparts		
- Hydrogen Reduction of Ilmenite	Fe, O2	350 t Fe
- Carbothermal Reduction	Si, O2	58 t Si
- Hydrogen Sulfide Reduction	Fe, O2	125 t Fe
- Carbochlorination	Al, Si, O2	48 t Al, 50 t Si
- HF Leach	Al, O2	16 t Al
- Reduction by Li or Na	Si, Fe, Ti, O2	70 t Si, 45 t Fe, 10 t Ti
- Reduction by Al	Al, Si, O2	42 t Al, 44 t Si
- Direct Fluorination of Anorthite	Al, Si, O2	48 t Al, 50 t Si
"Space-based" Processes		
- Magma Electrolysis	Fe, O2	350 t Fe
- Fluxed Electrolysis	Al, Si, Fe, O2	21 t Al, 62 t Si, 40 t Fe
- Solar Wind Gas Extraction	CH4, CO, O2	69 t CH4, 82 t CO
- Vaporization/Fractional Distillation	Al, Si, O2	19 t Al, 58 t Si
- Selective Ionization	Al, Si, Fe, Ti, O2	17 t Al, 50 t Si, 32 t Fe, 8 t Ti

Since this study included candidate propellant constituents that could be combined with LOX, the amounts of recovered LOX and metal (e.g., for a metal gel) must be balanced to meet the desired propellant mixture ratio. The amounts listed are computed from amounts available in the beneficiated feedstock; this accounts for process limitations, but does not account for component inefficiencies. A discussion of each candidate processing scheme follows.

Hydrogen Reduction of Ilmenite. This process has been demonstrated for lunar application by Carbotek Inc. in Houston, TX (Gibson and Knudsen 1985) and is currently the most widely discussed approach for lunar oxygen production. A process flow diagram is shown in Figure 3-5. The ilmenite feedstock, which is composed of iron and titanium oxides, is obtained through either electrostatic or magnetic beneficiation of collected lunar regolith. Hot hydrogen gas (~900° C) is then reacted with the ilmenite in a fluidized bed reactor to produce water vapor. The water vapor is then collected and electrolyzed to obtain the desired oxygen product. The electrolysis process also recovers the hydrogen reagent in gaseous form for reuse. Limitations inherent in this process are the low ilmenite content in lunar regolith (typically 5-15%), and the inability to remove any oxygen from the titanium dioxide separated by the reactor. The process is thus very inefficient in that it can only recover a small part of the oxygen known to be available in regolith. Hydrogen reduction is also unable to separate metals; iron could be recovered, but only with additional processing of the reacted solid mixture.

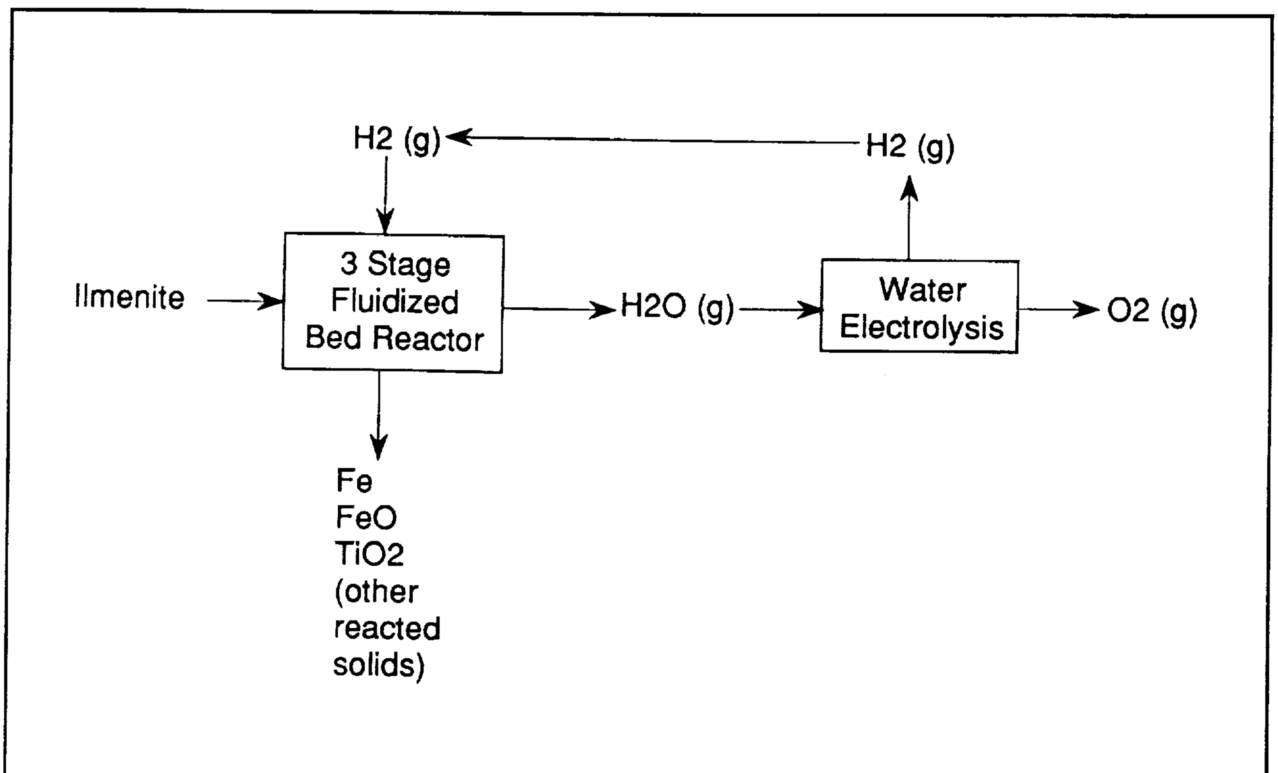


FIGURE 3-5: Hydrogen Reduction of Ilmenite

Carbothermal Reduction. This process has been studied by S. Rosenberg of Aerojet-General Corp. since the mid-1960's (Rosenberg 1966) and laboratory experiments have been performed using magnesium silicate. The process flow, using magnesium silicate feedstock, is shown in Figure 3-6. It is likely that most metallic silicates existing in lunar material could also be used as feedstock, but process requirements have only been determined using magnesium silicate. The reaction of methane with the metallic silicate occurs at a temperature of 1625° C, and produces carbon monoxide and hydrogen gases. These gases are reacted over a nickel catalyst to regenerate the methane reagent and produce water, from which the oxygen is obtained. The solid products from the metallic silicate-methane reaction include metal oxides, silicon, and silane. The major limitations of this process are the need to recover the methane reagent and the relatively high reaction temperatures required.

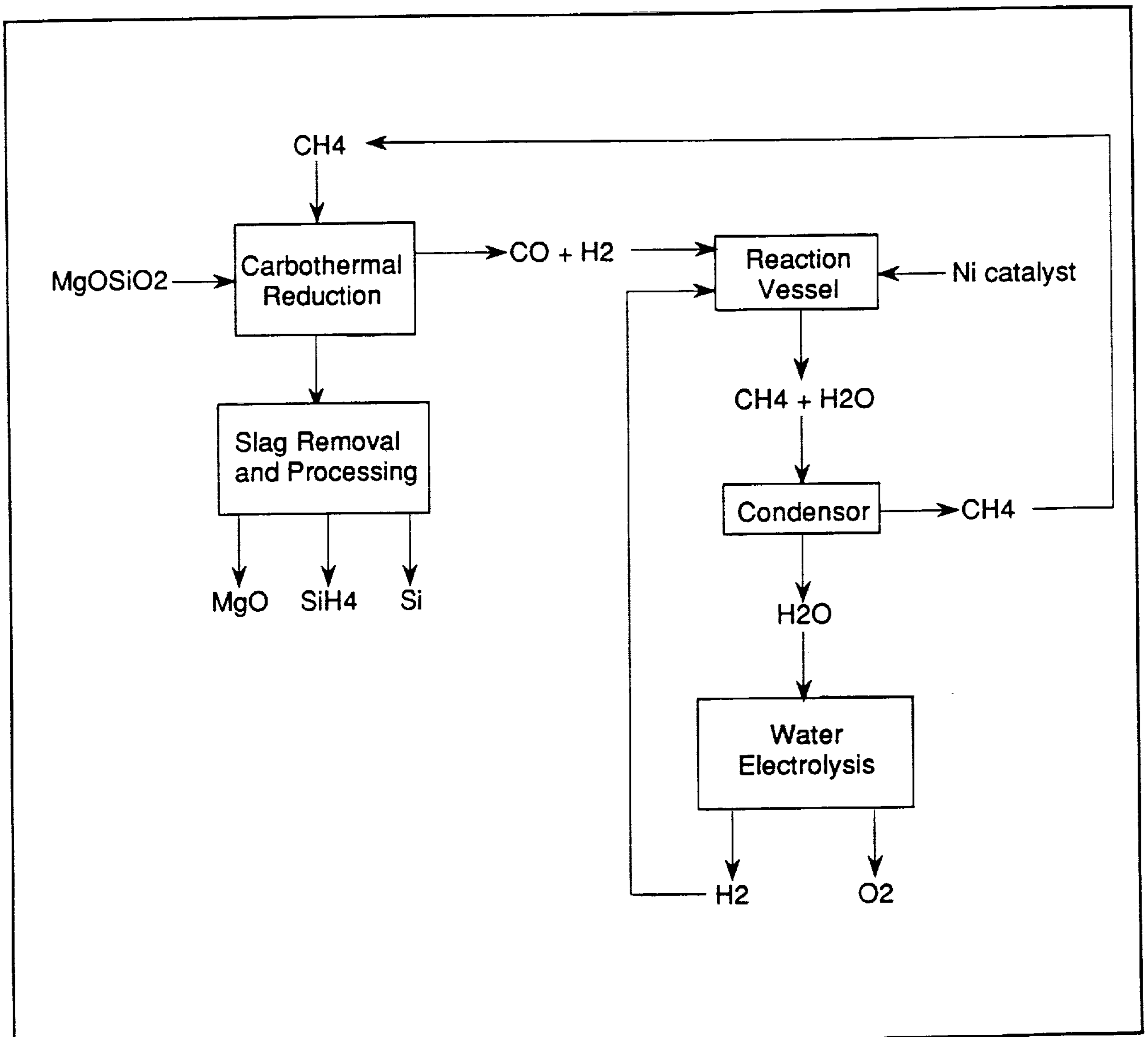


FIGURE 3-6: Carbothermal Reduction of Magnesium Silicate

Hydrogen Sulfide Reduction. Hydrogen sulfide reduction is very similar to the hydrogen reduction process. Its major advantage over hydrogen reduction is the ability of hydrogen sulfide to extract oxygen from calcium and magnesium oxides in addition to iron oxide. This attribute enables a greater oxygen yield per unit mass of lunar regolith. A major disadvantage is that the beneficiation technology required to isolate these oxides is yet unknown. A process flow diagram is shown in Figure 3-7.

Carbochlorination. Rao et al. (1979) proposed a carbochlorination scheme for producing aluminum and oxygen from lunar anorthite. A process flow diagram is shown in Figure 3-8. A major advantage of this system for aluminum production is the utilization of the Alcoa electrolysis process for separation of aluminum from aluminum chloride. Alcoa spent 15 years developing this process, now used to produce 15,000 tons of aluminum each year. The process is more complex than other candidates because reagents must be recovered for reuse. The carbochlorination reaction occurs at a relatively moderate 675-770° C (to avoid

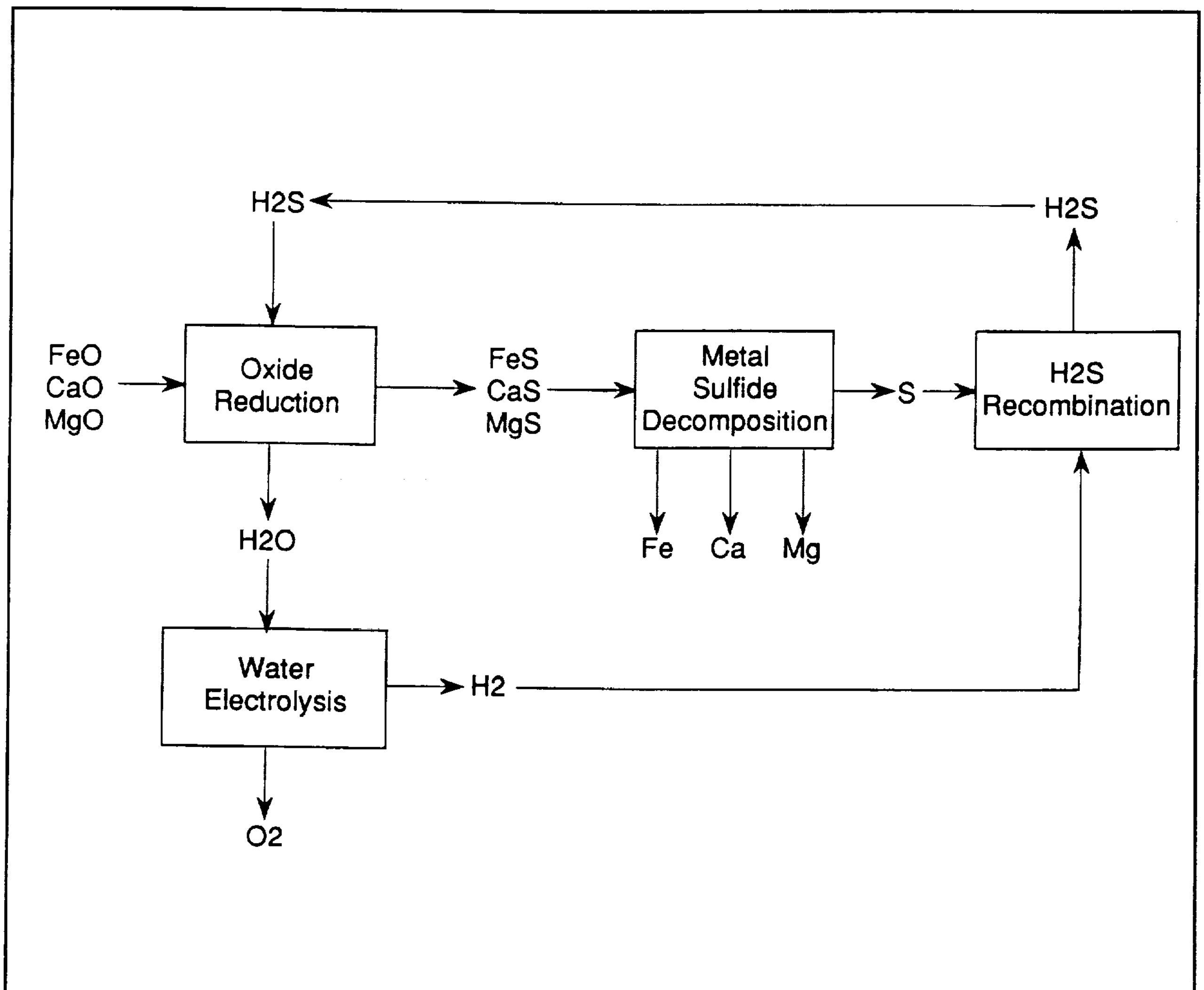


FIGURE 3-7: Hydrogen Sulfide Reduction

melting calcium chloride, which would complicate the operation). Carbon and chlorine react with anorthite to produce aluminum chloride and carbon monoxide. Oxygen and carbon are recovered from the carbon monoxide. Chlorine is recovered during aluminum chloride electrolysis and is also recovered to a certain degree from the silicon and calcium chlorides produced.

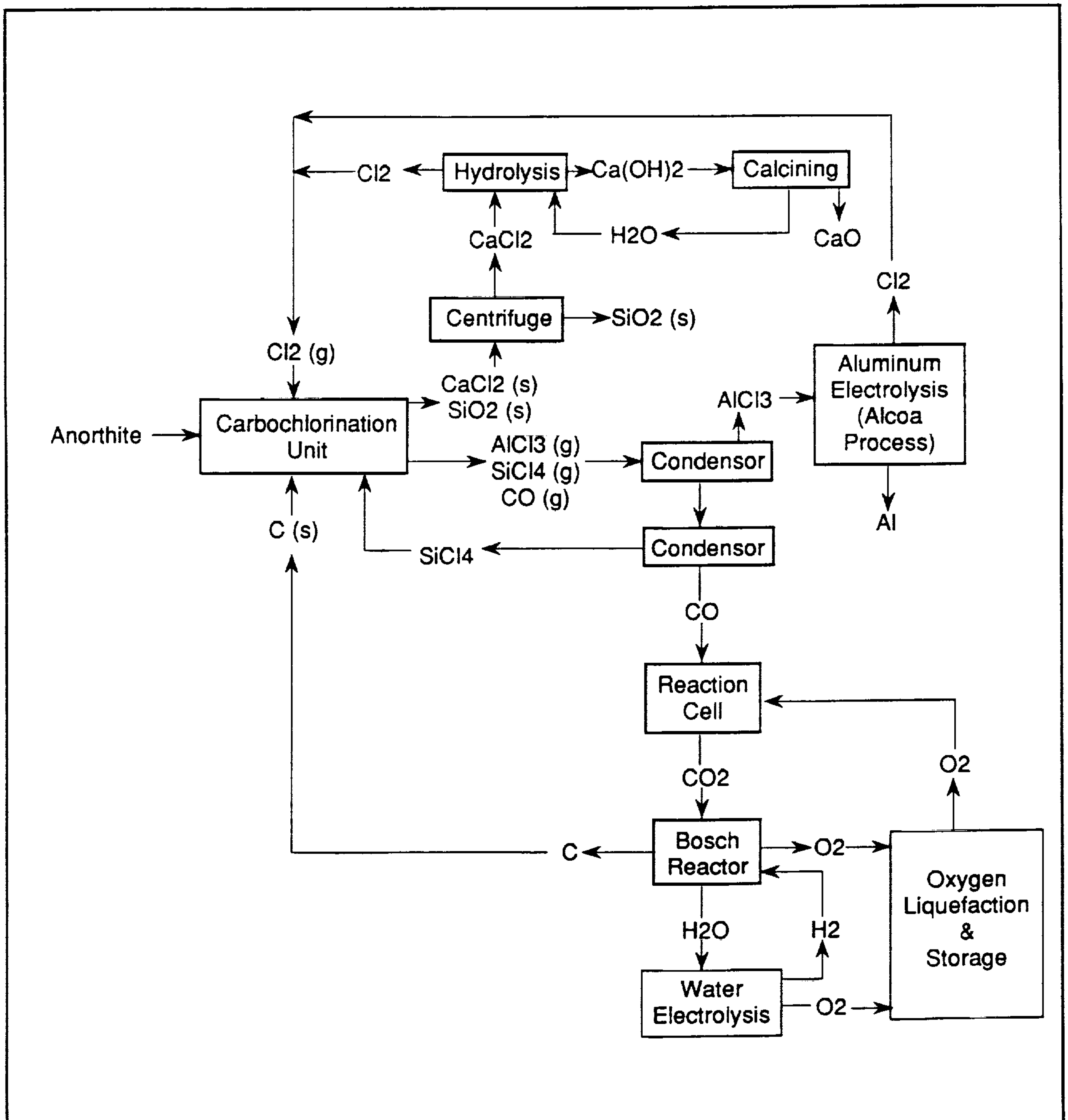


FIGURE 3-8: Carbochlorination of Anorthite

Hydrofluoric Acid Leach. Laboratory investigations using HF acid to dissolve and react with lunar soil at low temperatures (110° C) to produce mixed metal fluorides and water have been performed by R. Waldron of Rockwell International (Waldron 1985). Although fluorination of all lunar oxides appears possible, many complex operations are required to separate the metal fluorides and to recover the HF reagent. The process, as proposed by Waldron, utilizes 78 process modules, excluding external support systems. Sodium is used to reduce aluminum fluoride for aluminum production. Iron can be obtained through electrolysis of iron fluorosilicate, and magnesium can be obtained through reduction by silicon and calcium oxide. Figure 3-9 is a process flow diagram detailing only aluminum and oxygen production steps. If only aluminum and oxygen are desired, beneficiation of regolith to isolate the anorthite component would reduce reagent recovery requirements.

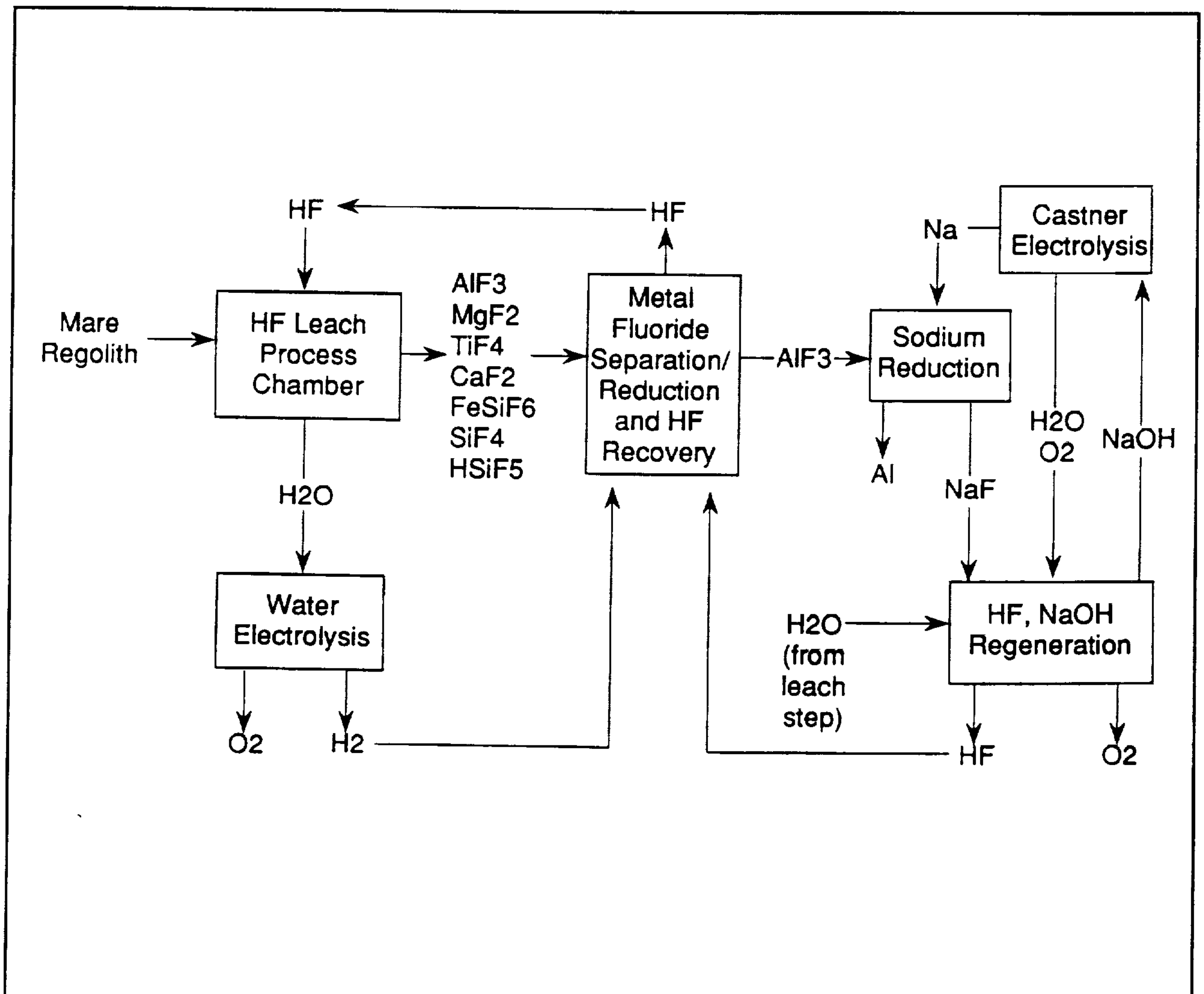


FIGURE 3-9: Hydrofluoric Acid Leach (Simplified)

Reduction by Li or Na. A process using lithium or sodium to reduce metal oxides was proposed by Sammells and Semkow (1988). A process flow diagram is shown in Figure 3-10. Reduction of iron, titanium, and silicon oxides is expected, but aluminum, calcium, and magnesium oxides will remain unreduced. Since silicon oxide appears to make up over 40% of the lunar regolith, this process has an advantage over hydrogen reduction schemes that use only ilmenite feedstock. Further study is needed to determine how the metals, metal oxides, and lithium oxide can be removed and separated from the lithium reduction step. Other issues to be addressed are material problems in the lithium oxide electrolysis cell, which operates at 900° C, and stability of the $LiF/LiCl/Li_2O$ electrolyte over long term operation.

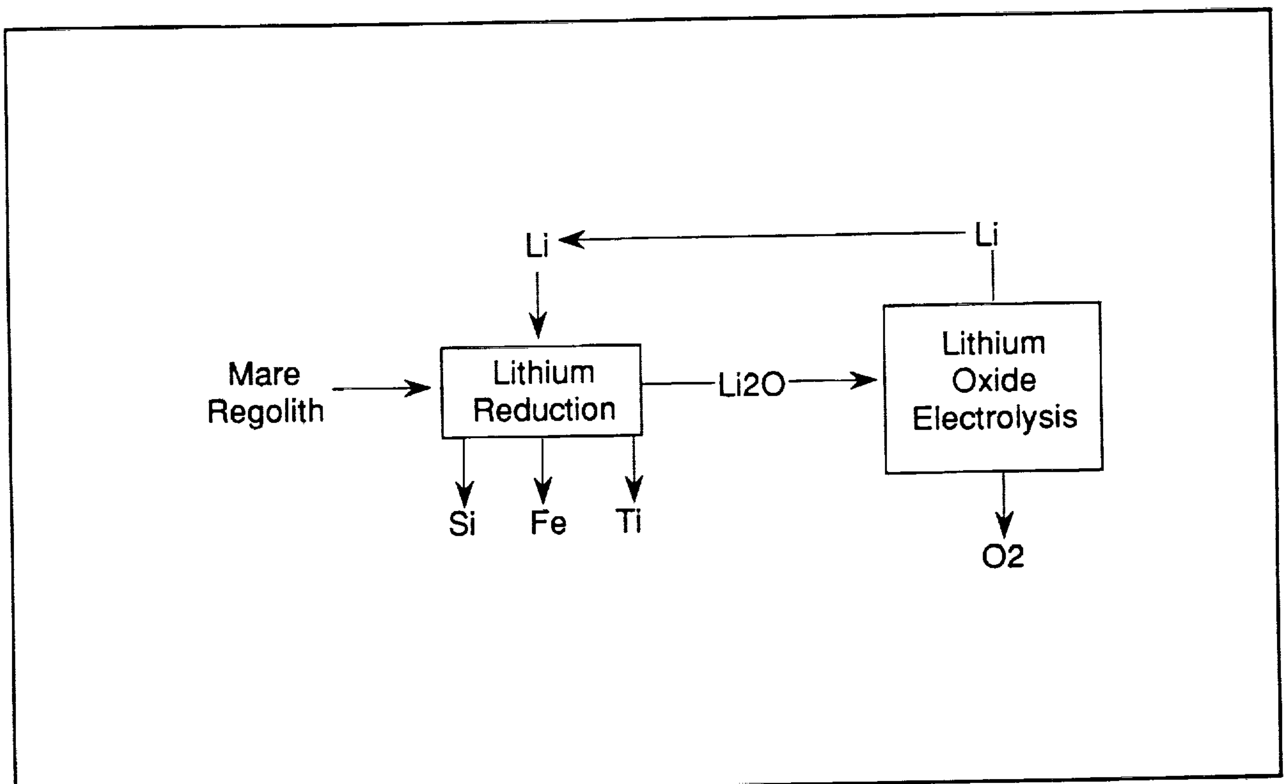


FIGURE 3-10: Reduction by Lithium

Reduction by Al. Figure 3-11 shows the reduction and electrolysis steps required to obtain silicon, aluminum, and oxygen from anorthite. This process was proposed by EMEC Consultants at the 2nd Symposium on Lunar Bases and Space Activities of the 21st Century (Anthony et al. 1988). After anorthite is dissolved in cryolite at about 1000° C, aluminum is added to reduce silica to silicon. After the silicon is removed, the cryolitic solution is transferred to an aluminum electrolysis cell where alumina is reduced, and aluminum and oxygen are obtained. The cryolitic solution is then transferred to a calcium electrolysis cell where calcium oxide is reduced, calcium and oxygen are obtained, and the cryolite is recovered. Experiments on the initial aluminum reduction step have been performed by EMEC Consultants. Development efforts are currently underway by the Department of Energy for anode materials used in the high temperature aluminum electrolysis step. Efforts are needed to determine requirements for recovery of the cryolite flux and to identify optimum operating conditions.

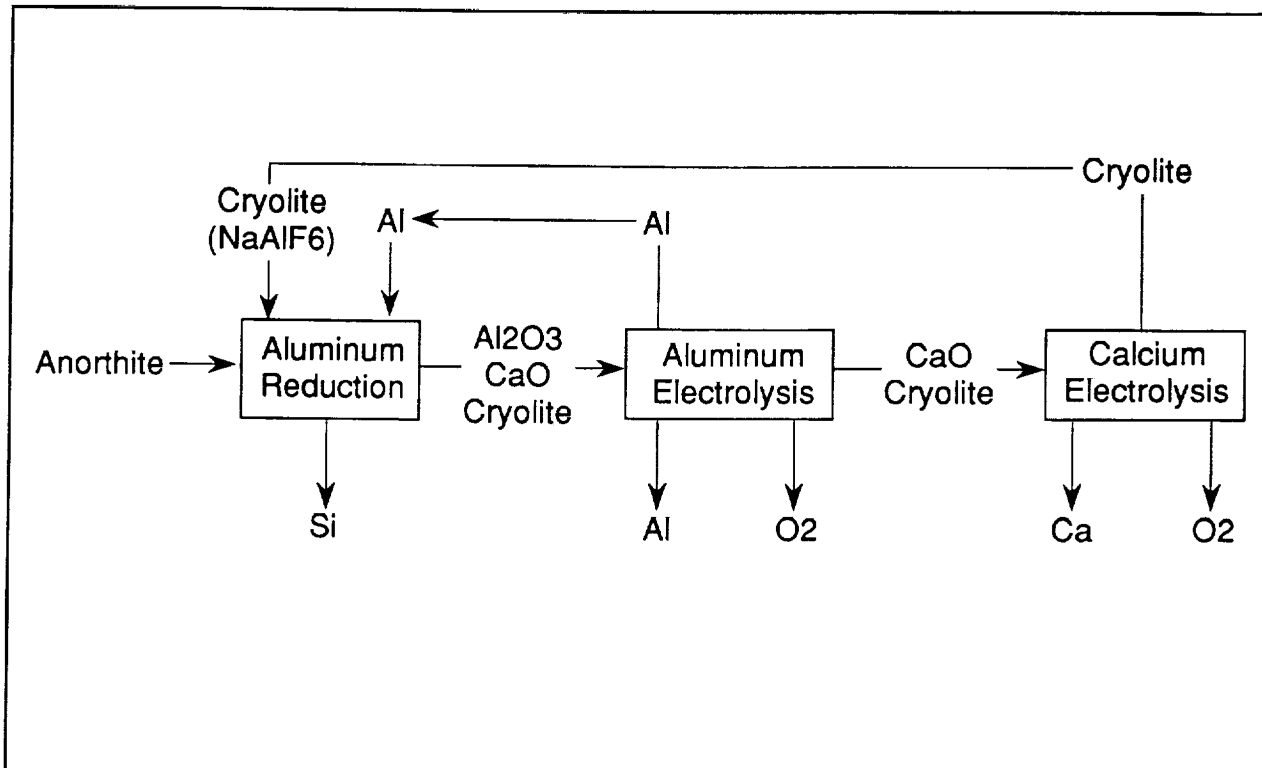


FIGURE 3-11: Reduction of Anorthite by Aluminum

Direct Fluorination of Anorthite. The use of fluorine for production of metals and oxygen from lunar materials was first presented by Dalton and Hohmann (1972). This oxygen production scheme was rejected by Dalton and Hohmann because of anticipated problems controlling the fast reaction rates predicted. However, a recent study by Burt (1988) looked at this problem as an advantage, given proper system design. A process flow diagram (de ed from Burt's work) is shown in Figure 3-12. Further research is required to assess operational chara cteristics and define material problems and potential production rates. Central to the feasibility of operation of this process is the ability to separate sodium and fluorine through NaF electrolysis, which is currently unproven.

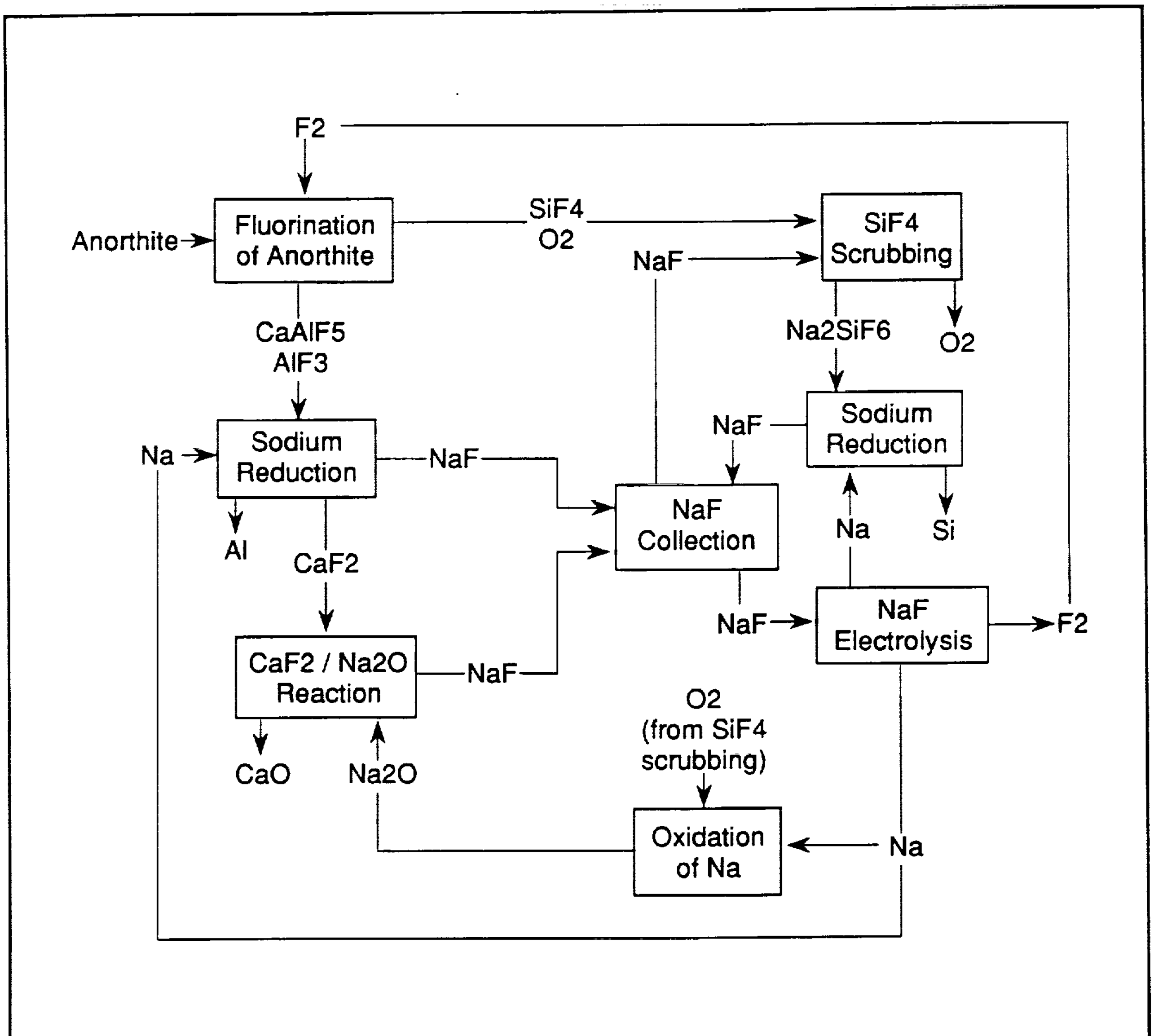


FIGURE 3-12: Direct Fluorination of Anorthite

Magma and Fluxed Electrolysis. Electrolysis processes are attractive for extracting oxygen and metals from lunar materials because so few steps are required. In terrestrial operation, most electrolysis cells utilize fluxing agents to lower viscosity and alter reduction voltages required. Also, most terrestrial electrolysis operations for metal recovery employ consumable anodes to increase the driving force of the reaction or to avoid the expense of developing a permanent anode that could withstand the high temperature and corrosive environment. Two options have been investigated for lunar application, and the general flow diagram for each of these is shown in Figure 3-13. The first was studied by Kesterke (1971); electrolysis was performed on metal silicate rock material dissolved in a mixed fluoride flux, demonstrating the ability to extract oxygen from silicate rock. Other studies claimed addition of fluxing agents could potentially extract many metals, such as aluminum, silicon, and iron, as well as oxygen. A second option was studied by Lindstrom and Haskin (1979) and by du Fresne and Schroeder (1983). This process employed no fluxes or consumable anodes. Their studies proved that sufficient conductivity could be realized in a silicate rock melt to produce oxygen and possibly iron. If suitable anode, cathode, and container materials could be found, other lunar elements could be electrolytically extracted without fluxing agents or consumable electrodes.

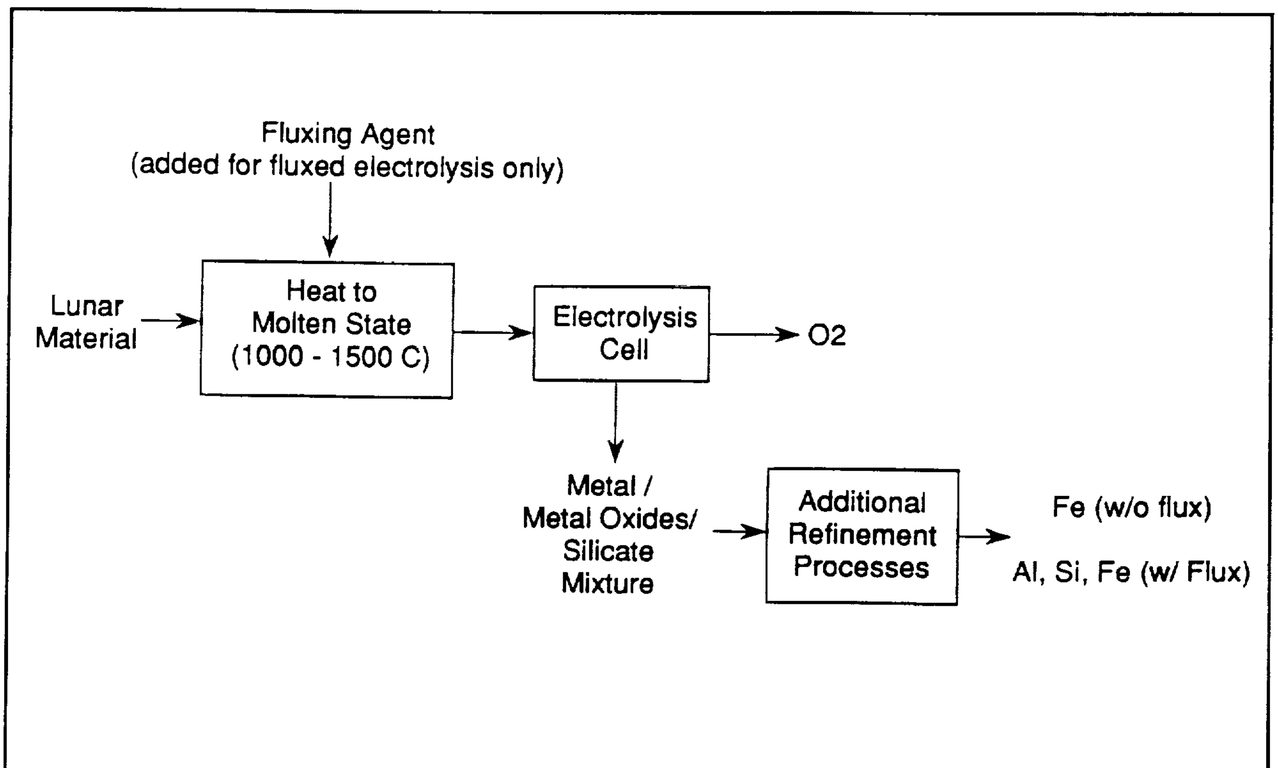
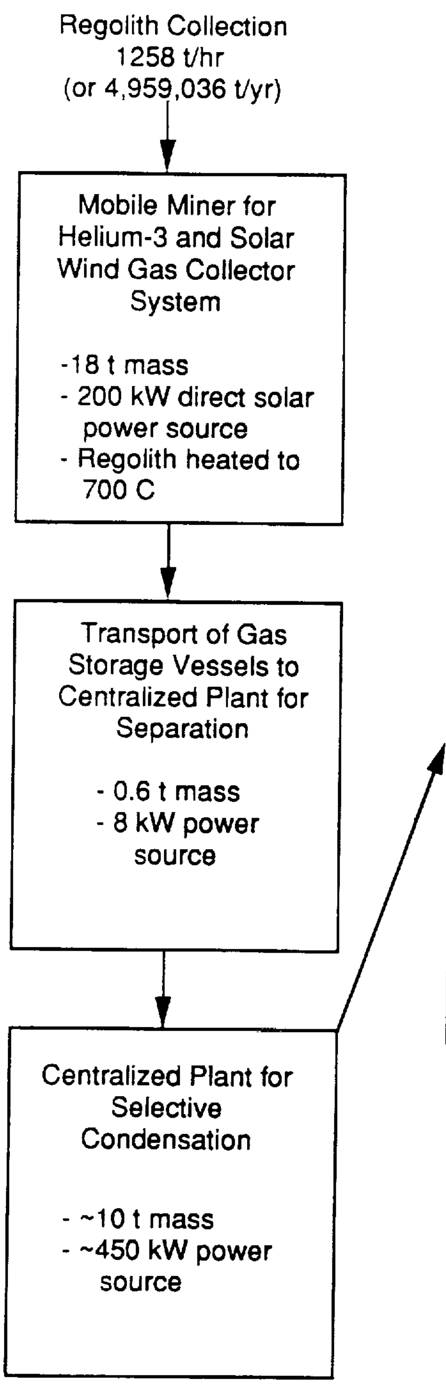


FIGURE 3-13: Magma and Fluxed Electrolysis

Solar Wind Gas Extraction. Thermal release studies of lunar samples have determined the gas release patterns occurring during heating to 1400° C (Gibson and Johnson 1971). Researchers at the University of Wisconsin (Wittenberg 1986) first investigated systems to remove these solar wind gases from regolith to obtain helium-3 -- a fusion fuel source with a limited terrestrial supply. Although concentration of helium-3 in lunar regolith is estimated to be only about 9 ppb, systems designed to extract helium-3 would also obtain significant quantities of the other solar wind gases, and at lower processing temperatures. Figure 3-14 summarizes the University of Wisconsin's concept and shows the predicted quantities of gases obtained during the course of mining for helium-3. Further definition of this mining system can be found in a paper by Sviatoslavsky and Jacobs (1988). The major technology driver for this process is the ability to heat lunar regolith to 700° C and pull off the evolved gases at a sufficient rate for collection of significant quantities of solar wind gases.

Of the processes discussed so far, this is the only one with the potential to obtain a propellant combination that could also be recovered from the Mars atmosphere: methane or carbon monoxide fuel, to be mixed with LOX. This process can be optimized for production of either methane or carbon monoxide. Examples of potential annual yields in schemes optimized for methane and carbon monoxide production are shown in Figure 3-15. The technologies employed here are similar to methane or carbon monoxide production systems that use the Mars atmosphere. It should be noted that the volatile extraction studies to date have not estimated the requirements for the subsequent gas processing for optimization of lunar methane or carbon monoxide production or the additional requirements on a mobile solar wind gas mining system to employ hydrogen reduction.



Products	Mass/yr	Notes
H_2	201.3 t	Removed prior to condensation with palladium membranes
CO_2	56.1 t	Removed @ ~ 190 K
CH_4	52.8 t	Removed @ ~ 115 K
CO	62.7 t	Removed @ ~ 80 K
N_2	16.5 t	Removed @ ~ 75 K
He	102.3 t	
He-3	33 kg	Removed from He with super leak system (@ 1.5 K)

FIGURE 3-14: Process Flow for Volatile Collection on the Moon

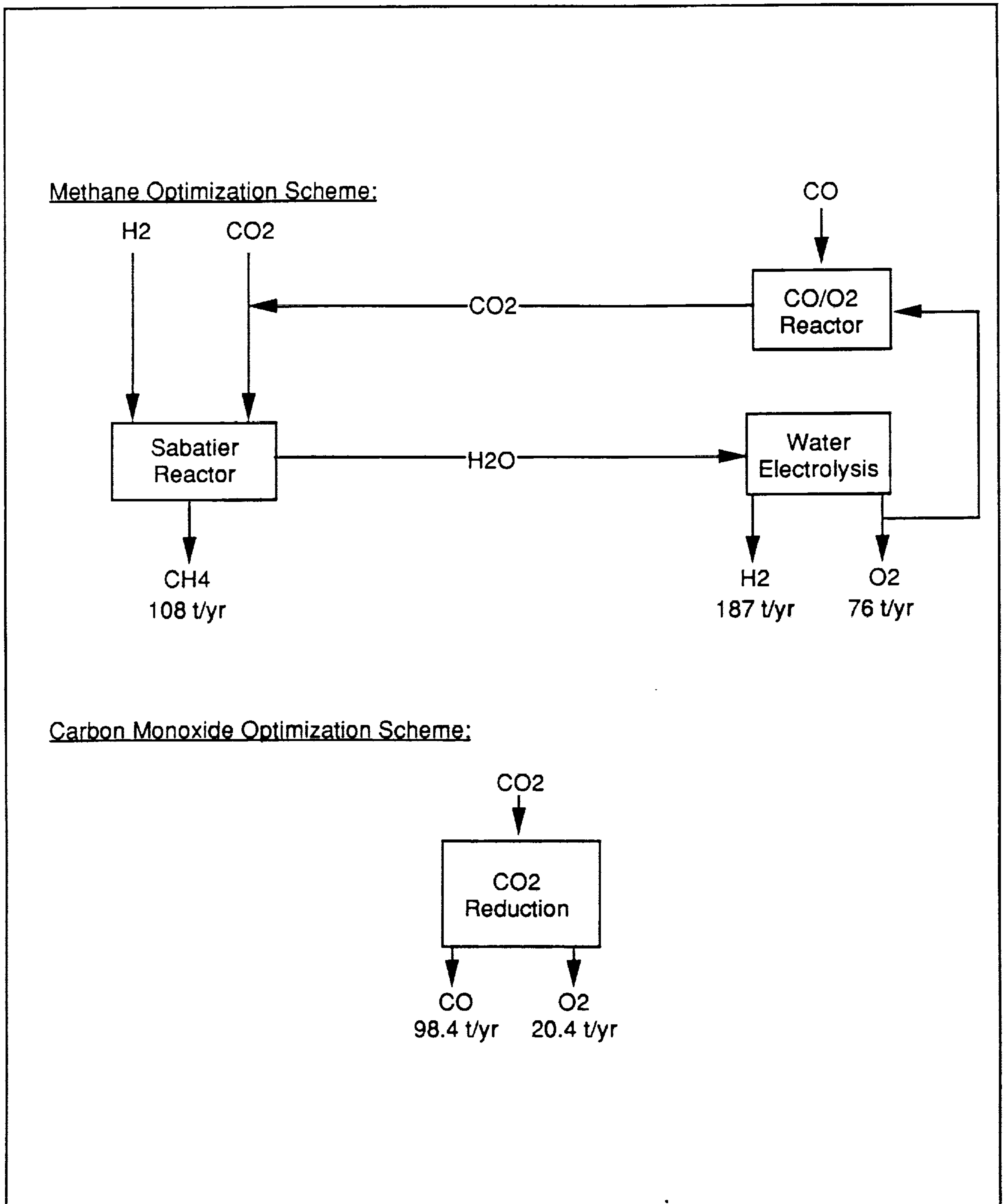


FIGURE 3-15: Solar Wind Gas Extraction Options

Vaporization/Fractional Distillation. This process, studied by Steurer and Nerad (1983), introduces a new concept of extractive metallurgy specifically suited for space-based processing. Figure 3-16 shows the flow diagram for this process. Raw lunar material is vaporized and further heated to the point of dissociation; substantial amounts of oxygen are set free. The vapor, consisting of a mixture of oxides and suboxides, is rapidly cooled to condense and remove these oxides and suboxides while the oxygen remains gaseous, to be collected downstream. The study indicates that the optimum temperature for this dissociation is about 3000 K, which allows the use of direct concentrated solar energy. Theoretical studies show that approximately half of the oxygen in silicon, titanium, and aluminum oxides can be removed, although iron oxide is not dissociated. Upon analysis of the chemistry involved with the condensation of suboxides, it appears that production of free aluminum and silicon is possible. The process makes use of the lunar environment's vacuum to provide a pressure gradient to rapidly move the gases through the system. It is estimated that 30,000 kWh of energy would be required for every ton of oxygen collected.

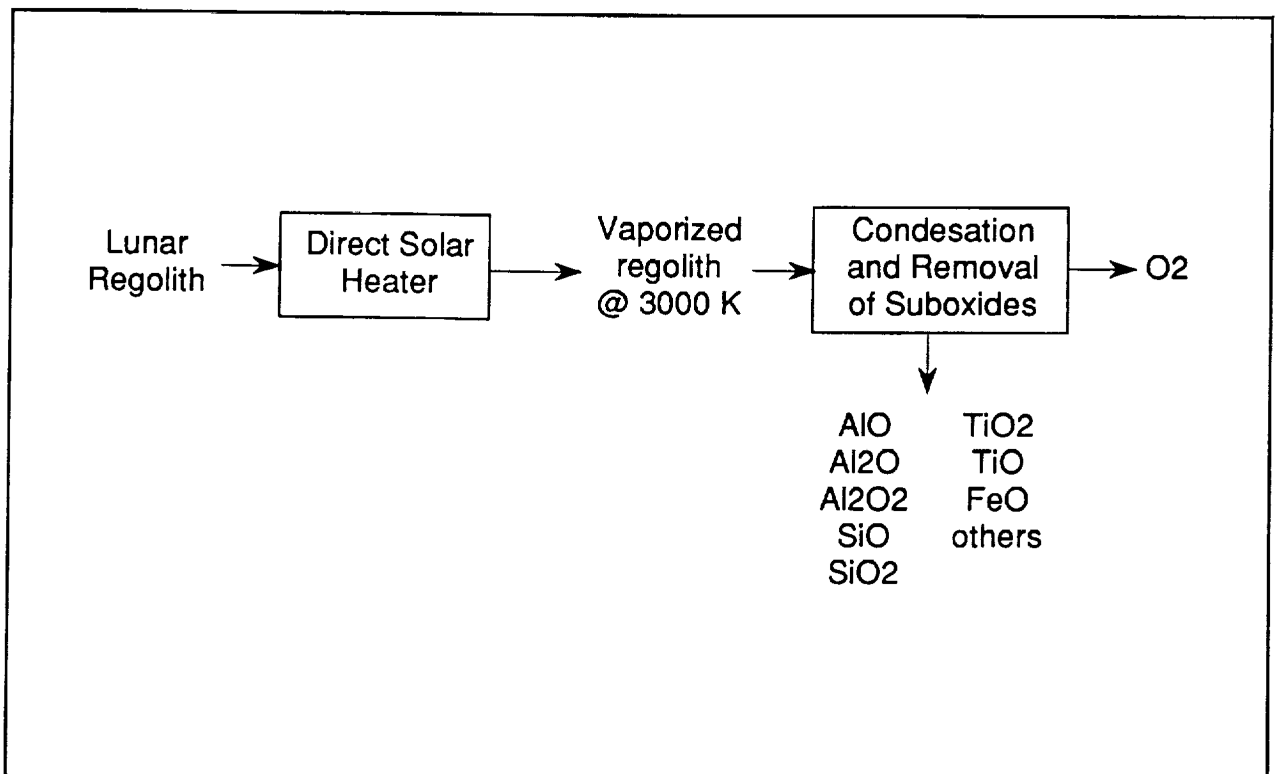


FIGURE 3-16: Vaporization/Fractional Distillation

Selective Ionization. Realizing that at higher temperatures, further dissociation takes place and that within a certain temperature range, most metals would be almost entirely ionized while oxygen remains essentially neutral, Steurer and Nerad (1983) proposed selective ionization as a candidate process for oxygen and metal recovery. In this process, shown in Figure 3-17, raw lunar material is passed through a thermal plasma and heated to 8000 K where titanium, aluminum, magnesium, iron, and silicon are ionized. This gas mixture, also containing neutral oxygen, is passed through either an electromagnetic or electrostatic field where the metals are removed from the gas flow, and oxygen is collected downstream. It is theoretically possible for the ionized metals to be separated during the application of an electrostatic or electromagnetic field, although past work on this subject is limited. Further experimentation is likely to encounter extreme material problems due to the high temperatures involved.

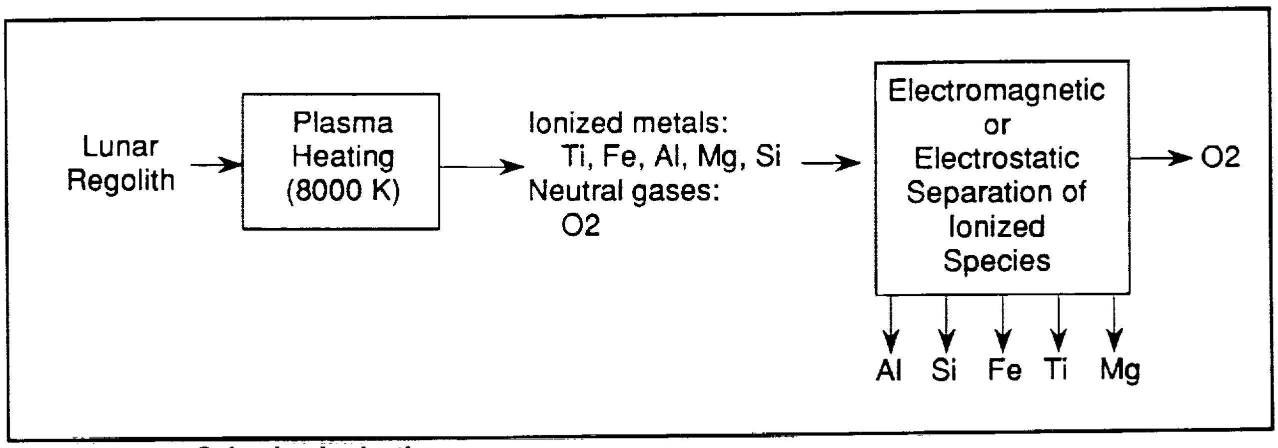


FIGURE 3-17: Selective Ionization

Evaluation of Processing Alternatives

The amount of research available on each of the lunar-based propellant processing candidates varies; therefore, estimating a propellant production plant's requirements is not a straightforward process. Although many of the candidates are based on terrestrial analogues, application of these techniques in the lunar environment is very likely to introduce new technology requirements. Also, many of the candidates use feedstocks that may not be readily isolated from bulk lunar material. Mining and regolith excavation are required by all the candidates, and the impacts of operating all hardware systems over long periods of time in a vacuum and in the presence of very fine grained, abrasive regolith particles must be addressed.

In assessing the performance of the processing alternatives discussed, we focused on identifying the more readily accessible propellant combinations, not on selecting the optimum process. Initial attempts were made to qualitatively examine operational and development issues for each process candidate's ability to obtain various propellant combinations. However, the large error bars associated with almost every estimate of engineering requirements, and the subjective nature of such an evaluation, combine to make process selection too arbitrary; more definition of candidates is required before a reasonable decision can be made.

Data from the literature will be presented in terms of feedstock, plant mass, energy, and reagent resupply requirements per unit mass of fuel obtained, assuming oxygen to be the oxidizer for all propellant combinations. Table 3-4 cites the references used for each of the processes considered. In order to gain a better perspective on the fidelity of the data presented, estimates of technology readiness, using the readiness levels defined by the NASA Office of Aeronautics, Exploration and Technology, will also be presented followed by a discussion of the accessibility of each propellant combination under consideration.

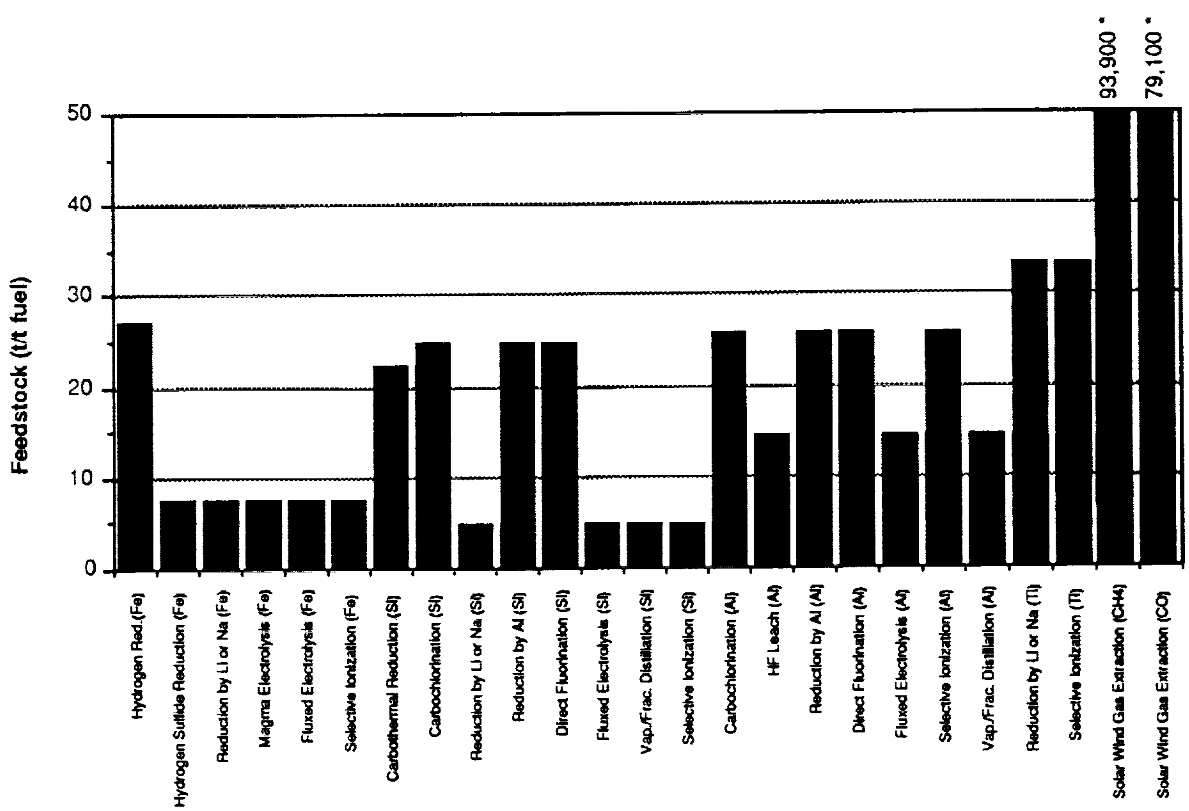
TABLE 3-4
SOURCES FOR PROCESS DESCRIPTION

PROCESS	LITERATURE SOURCE
Hydrogen Reduction of Ilmenite	Christiansen (1988)
Carbothermal Reduction	Astronautics Corp. of America (1987)
Hydrogen Sulfide Reduction	Dalton and Hohmann (1972)
Carbochlorination	Astronautics Corporation of America (1987)
HF Leach	Astronautics Corporation of America (1987)
Reduction by Li or Na	Sammells and Semkow (1988)
Reduction by Al	Anthony et al. (1988)
Direct Anorthite Fluorination	Dalton and Hohman (1972)
Magma Electrolysis	Astronautics Corporation of America (1987)
Fluxed Electrolysis	Dalton and Hohman (1972)
Solar Wind Gas Extraction	Sviatoslavsky and Jacobs (1988)
Vaporization/Frac. Distillation	Steurer and Nerad (1983)
Selective Ionization	Steurer and Nerad (1983)

Summary of Process Performance

The primary objective of all these processing concepts is to produce oxygen. Most alternatives can recover much more oxygen than a specific metal, so process output requirements were calculated from the amount of metal required for a selected mixture ratio. Most of the processes have been defined starting with a beneficiated feedstock and ending with the separation of resources. Excavation/beneficiation, product collection/storage, and power system requirements were estimated separately.

Feedstock Requirements. The feedstock requirement is an indication of how much lunar material must be collected to obtain a certain amount of a given resource. The requirement is driven by resource concentrations on the lunar surface and by limitations of the various processing approaches. Figure 3-18 is a comparison of the theoretical feedstock requirements. These estimates should be viewed as lower bounds for all process candidates. Actual feedstocks required will be affected by the efficiency of the



* Feedstock requirement could be reduced to 45,900 t/t methane or 50,400 t/t carbon monoxide with subsequent processing using other volatiles collected.

FIGURE 3-18: Process Feedstock Requirements

regolith beneficiation system, as well as by process subsystem efficiency losses. Better insight into design issues will likely increase these values; however, the values shown here should permit reasonable comparison of the processing candidates. The trends shown in Figure 3-18 generally follow the metal element abundances. Feedstock requirements are lower for silicon and iron (except for ilmenite reduction, which requires a beneficiated feedstock), and somewhat higher for less abundant aluminum and titanium. It is important to note that the solar wind gas extraction feedstock requirement is unique in that the collected lunar material is not transported to the processing plant but is partially processed in situ. In this process, only the collected mixture of volatiles is transported to the centralized processing facility.

An understanding of the required beneficiation allows better interpretation of the feedstock requirements comparison figure. Mineral separations involve the separation of ilmenite (for hydrogen reduction) from bulk regolith, and the separation of anorthite for three other processes (carbochlorination, Al reduction, and direct fluorination). Schemes have been investigated for mineral separation, but much research remains to be done to assess their feasibility. The two processes requiring separation of specific oxides or silicates from bulk regolith, carbothermal reduction and hydrogen sulfide reduction, were studied assuming this type of beneficiation to be possible. These candidates can also be used to process bulk lunar material or specific minerals, but reagent recovery requirements would then become excessive. The other processes do not require beneficiated feedstock to operate.

Plant Mass. Plant mass requirements are shown in Table 3-5. Of the 13 candidates considered for lunar material processing, plant mass estimates were available for eight. Lower plant mass is desirable, although plant mass by itself does not necessarily indicate the effectiveness of a given processing system. Issues such as hardware lifetimes and refurbishment requirements also affect the utility of a given candidate. The lack of data available for plant mass estimates illustrates the immaturity of resource processing designs.

TABLE 3-5
PLANT MASS REQUIREMENTS

PROCESS	PLANT MASS t/t output/yr	PROPELLANT
Hydrogen Reduction	0.066	LOX/Fe
Magma Electrolysis	0.003	LOX/Fe
Carbothermal Reduction	0.171	LOX/Si
Carbochlorination	0.220	LOX/Si
	0.230	LOX/Al
HF Leach	0.610	LOX/Al
Gas Extraction of CH_4	0.540	LOX/CH_4
Gas Extraction of CO_2	0.460	LOX/CO

Energy. Energy requirements have been estimated for all candidate processes considered here. Energy estimates for those processes where plant mass estimates were unavailable are preliminary and may change as system designs mature. Figure 3-19 shows the energy requirements for the candidates. Energy requirements for extraction of aluminum and titanium are generally higher than those for silicon and iron.

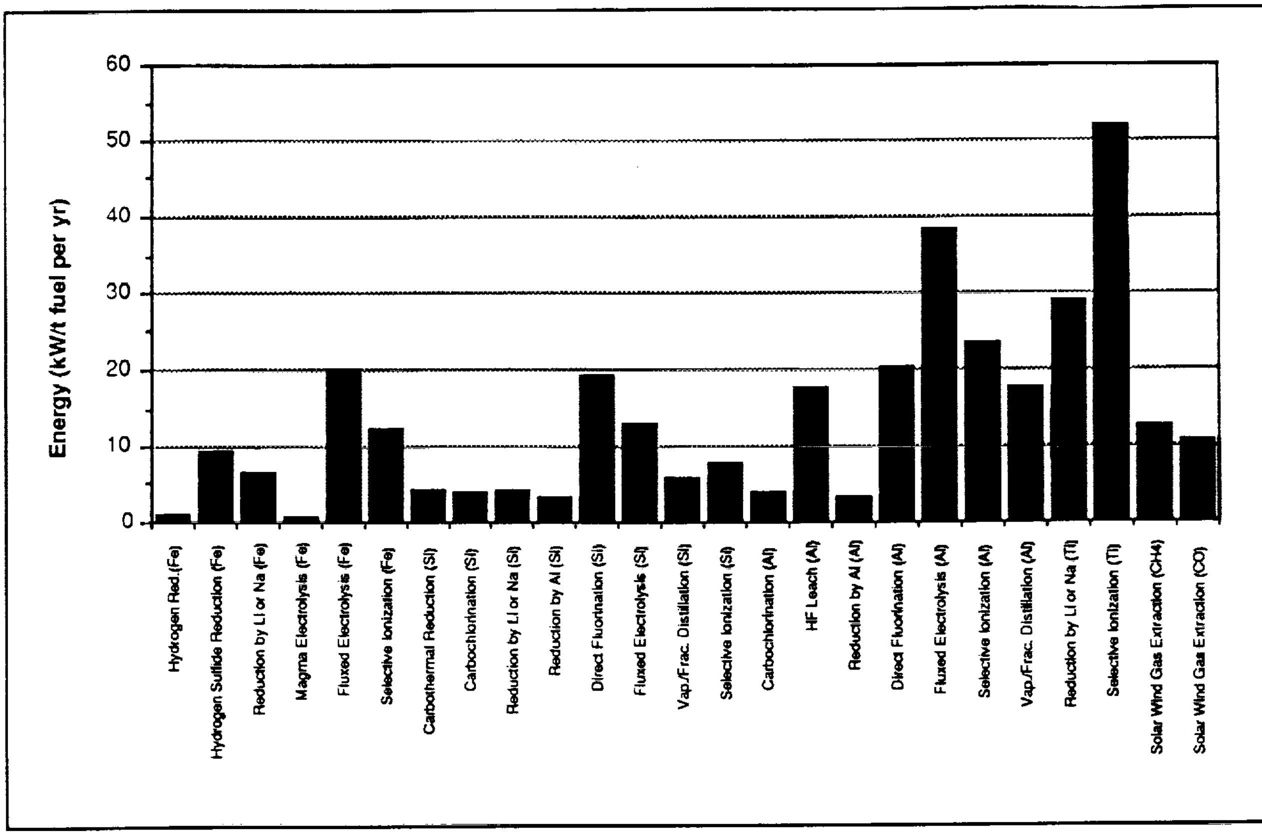


FIGURE 3-19: Process Energy Requirements

Reagent Resupply. Figure 3-20 shows the reagent replacement requirements derived from the literature. None of the "space-based" candidates use reagents and will not require resupply (except for hardware refurbishment). Of the remaining candidates, hydrogen reduction appears to have the minimum reagent replacement requirement and is so low compared to the other, non-space-based, candidates that it does not even register on the plot. The main reason for this is that this process utilizes a feedstock that only contains two oxides, iron and titanium oxides in the mineral ilmenite. All hydrogen used as a reagent is recovered during water electrolysis steps to obtain oxygen from iron oxide. Actual process experience under lunar conditions may show greater losses than realized in controlled laboratory experiments. The candidates with the higher reagent replacement requirements are those that utilize very reactive elements, chlorine and fluorine, and these tend to react with so many different elements in the feedstock that total recovery would significantly impact plant mass requirements. It is very difficult to compare reagent resupply requirements for many of the candidates until more operational experience is obtained.

Estimation of Plant Requirements

Because the definition of lunar propellant production requirements is still preliminary, plant requirements are dealt with parametrically, based on information presented in the literature. Figure 3-21 shows the generic flow diagram followed for most of the processing candidates and is included to show more clearly what

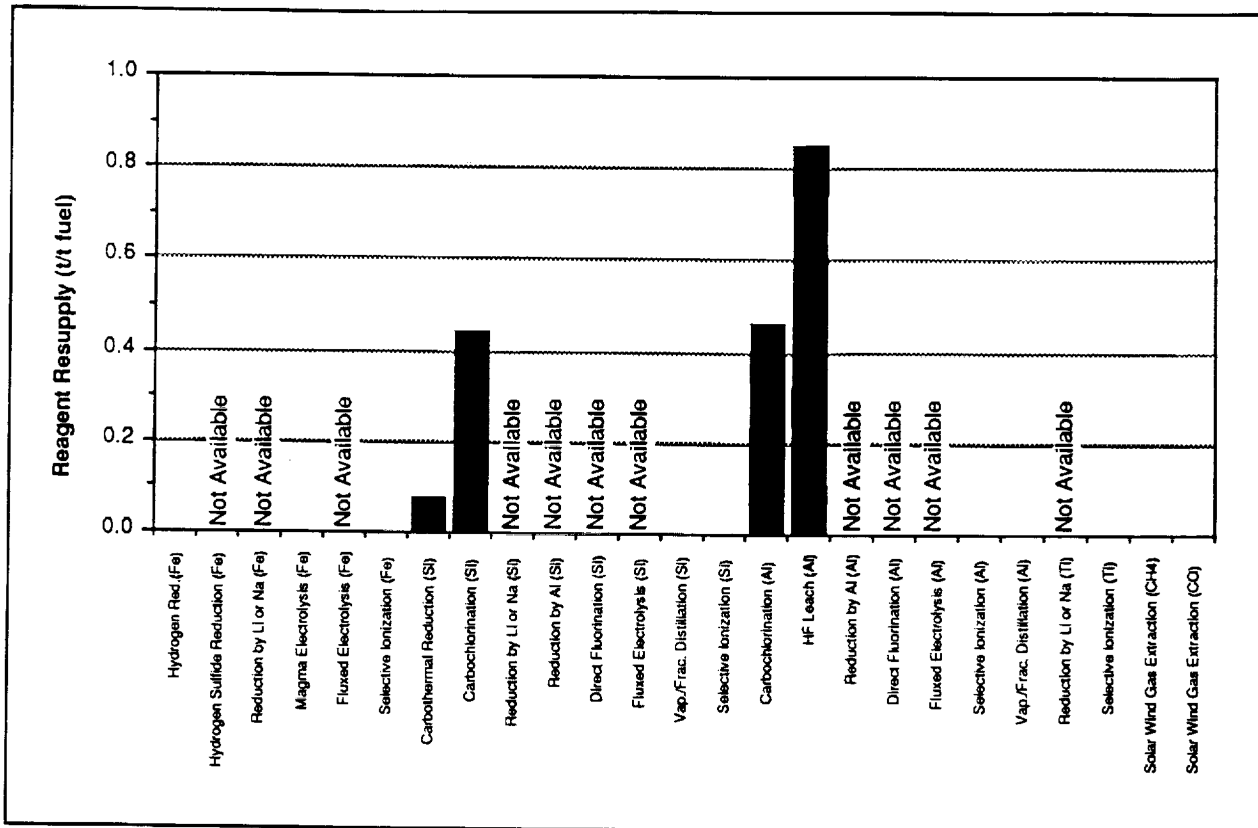


FIGURE 3-20: Reagent Resupply Requirements

makes up the plant requirements. The literature sources focus on the processing system and reagent recovery systems. We supplied estimates for regolith excavation/collection, feedstock beneficiation, and power sources.

A preliminary evaluation was made to reduce the set of alternative propellant candidates to better focus efforts toward defining plant mass and power requirements for the various propellant combinations under consideration. Seven propellant combinations, of which 5 are liquid-oxygen/metal gels and 2 are more conventional chemical bipropellants, are under evaluation in this study for support of space exploration. These candidate propellant combinations are: LOX/Fe, LOX/Si, LOX/Al, LOX/Al-Mg, LOX/Ti, LOX/CH_4, and LOX/CO. Some issues concerning the accessibility of each combination are discussed below.

LOX/Fe. Iron on the lunar surface is predominantly found in its oxide form, although a small percentage of free iron exists. A total of six candidate processes were identified as having the potential for extraction of iron. Of these alternatives for recovering iron, only hydrogen reduction requires beneficiation. However, the beneficiation process that isolates ilmenite also discards a significant quantity of iron oxide bound into other mineral forms, reducing its ability to efficiently produce iron. Magma electrolysis has received much attention as a potential system for oxygen and iron extraction from bulk lunar material with no beneficiation requirement and no reagent resupply. The main drawbacks of this alternative are selecting the material for

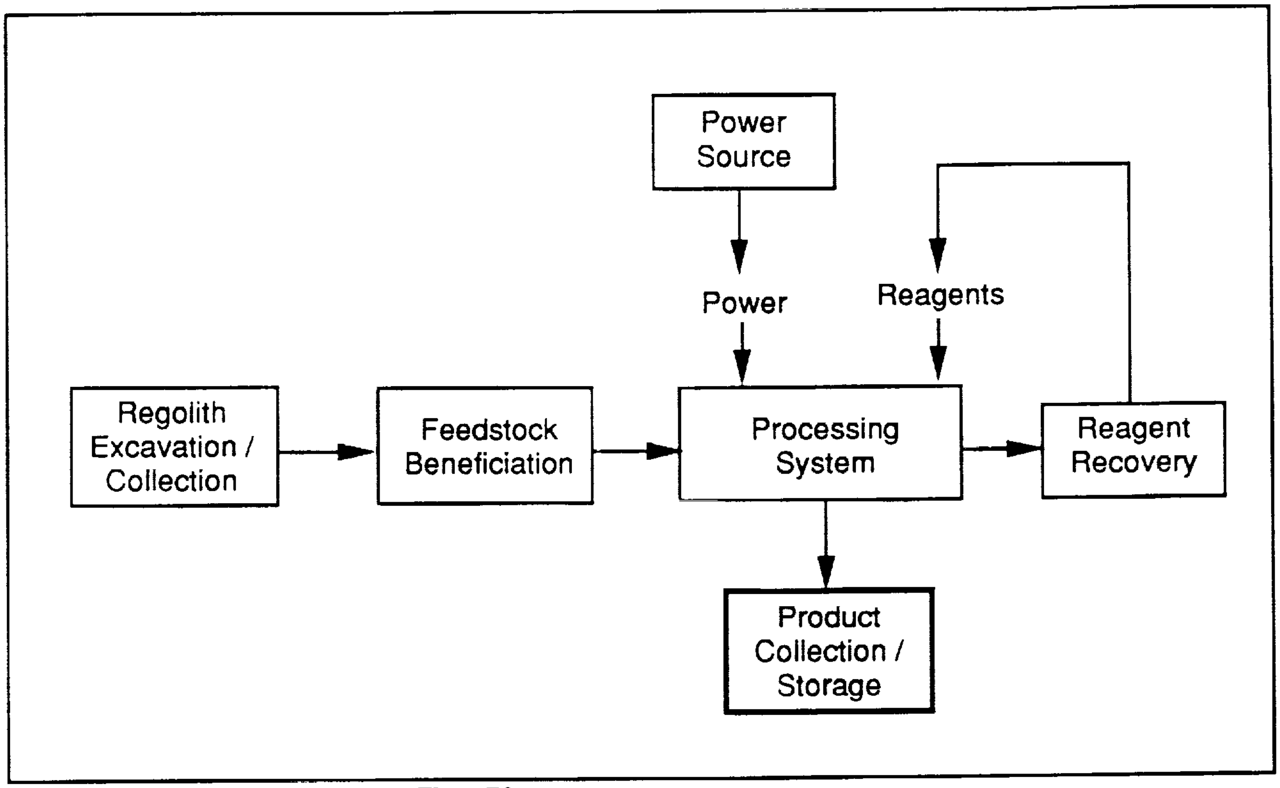


FIGURE 3-21: Generic Process Flow Diagram

electrodes, and maintaining conductivity in the melt. If these drawbacks could be overcome, magma electrolysis would be ideally suited for extraction of iron and oxygen. A majority of the remaining iron production alternatives have not been studied in enough detail to fairly evaluate their performance. Review of the literature suggests that iron production is less resource intensive than production of aluminum or titanium, and is comparable to silicon extraction, although iron is less concentrated in lunar material based on the sample analysis to date.

LOX/Si. Although eight alternative processes have been identified for silicon production, a majority of these processes were not designed to optimize extraction of silicon. Besides oxygen production, the production of metals for construction (not propellants) has been most thoroughly studied. Although silicon has a valuable use for solar cell production, few processes have focused on its extraction. The reason so many processes have been identified as potential silicon production candidates is that all lunar minerals except ilmenite are composed of metallic silicates. This would make the establishment of a LOX/Si production plant on the lunar surface much less sensitive to selection of a location, compared to extraction of titanium, iron, or aluminum. The literature suggests that the requirements for obtaining silicon are at least as low as for the other metal candidates, but many of the silicon production alternatives need additional research and experience to better assess their requirements.

LOX/Al. Seven candidates have been identified for producing aluminum. All except the vapor phase processes require reagents to reduce aluminum oxide to a form in which aluminum can be more readily extracted by reduction (by Li or Na) or by electrolysis. In all these cases, recovery of the input reagent is critical to efficient operation of the aluminum production plant. Aluminum production does appear more resource-intensive than iron or silicon production, but less intensive than titanium production. One of the main reasons so many of the processes have looked at production of aluminum is that there are many uses for it, assuming that a lunar base infrastructure is in place.

LOX/Al-Mg. Only one aluminum extraction process, selective ionization, has the potential to obtain both aluminum and magnesium; however, it is the most technologically immature of all candidates studied. It is likely that producing both aluminum and magnesium will require two separate processes, requiring more support and resources than for production of any of the other LOX/metal gel candidates.

LOX/Ti. Only two candidate processes have been identified for titanium production. Review of the literature suggests that extraction of titanium from lunar materials will require much more resources than extraction of aluminum, silicon, or iron. There are two reasons for this. The first is that titanium exists in lower concentrations than the other metals used in the LOX/metal gel candidates. The second is the stability of titanium oxide, which must be dissociated to obtain titanium.

LOX/CH_4. Extraction of methane or carbon monoxide cannot be fairly compared to the candidates for production of the LOX/metal gels. The major expenditure of resources for extraction of metals is the separation of the metals from metallic silicates or metal oxides. Extraction of solar wind implanted volatiles only requires energy which is a replenishable lunar resource if solar sources are utilized. The main expenditure of energy for extraction of methane is for heating the large amounts of lunar regolith and for cooling the collected gas mixture to condense out methane. In a scheme optimized for methane production, additional amounts of methane can be obtained through subsequent processing of carbon monoxide, carbon dioxide, and hydrogen, which are also collected from solar wind gas extraction. From a cost standpoint, the systems designed for production of methane would have significant commonality with systems designed for methane production at Mars. Also, this process can be operated with today's technology and has significant potential for automation.

LOX/CO. The extraction of carbon monoxide from lunar soils appears somewhat less resource intensive than extraction of methane if additional volatile processing is not considered. Utilizing the volatiles collected by a solar wind gas extraction system in a scheme optimized for carbon monoxide production does allow production of comparable amounts to the mass of methane obtainable, although significantly lower amounts of oxygen are obtained.

Based on accessibility issues, LOX/Ti and LOX/Al-Mg are the only two candidates that can readily be eliminated from further consideration. Another combination, LOX/Fe, seems comparable to the other candidates in terms of accessibility, but is significantly worse than any of the other candidates in terms of performance (to be addressed in Section 5 of this report). Therefore, propellant production plant requirements were estimated for only the following candidates: LOX/Si, LOX/Al, LOX/CH_4, and LOX/CO.

Four parameters were used to aid estimation of plant requirements: feedstock (in tonnes feedstock per tonne fuel obtained; plant mass not including regolith excavation/beneficiation, propellant storage, and power systems (in tonnes system mass per tonne fuel produced per year); energy (in kW power required per tonne fuel produced per year); and reagent resupply (in tonnes resupply per tonne fuel obtained). The goal of this analysis is to characterize requirements for utilization of specific lunar/Mars propellant candidates, not select specific processing alternatives. Therefore, two values (low and high) characterize each parameter for each propellant candidate. These values capture the range of quoted values from other studies, and do not represent any particular selection of processes. The assignment of these values is shown in Table 3-6.

TABLE 3-6
PLANT REQUIREMENTS RANGES

	Requirements							
	Feedstock (t/t_{fuel})		Plant Mass (t/t_{fuel}/year)		Energy (kW/t_{fuel}/year)		Reagent Supply (t/t_{fuel})	
Propellant	Low	High	Low	High	Low	High	Low	High
LOX/Si	5	25	0.2	0.3	5	20	0.02	0.03
LOX/Al	15	25	0.3	0.5	5	35	0.03	0.05
LOX/CO, LOX/CH_4	50K	100K	0.5	0.75	10	15	0	0

The values shown in the table for the LOX/Si and LOX/Al propellants include the processing hardware, reagent recovery, and resupply systems only; regolith collection, beneficiation, propellant storage, and power systems are not included. The "low" and "high" values for each parameter are taken from the lowest and highest estimates quoted in the reference material. Since reagent resupply estimates are unavailable from referenced studies, we assigned approximate values by selecting a reasonable lower limit for silicon production, adding an additional 50% to this value for the low value for aluminum (since aluminum is somewhat more energy intensive to produce than silicon, recovery of reagents used may be slightly more difficult). The high values for reagent resupply each add an additional 50% to the corresponding low values. Subsequent performance analysis will characterize requirements for each propellant in terms of the low values presented here. The question of surface element sizing will require much more study to improve the accuracy and utility of the values shown.

Separate estimates must be made for regolith collection/beneficiation, propellant storage, and power system requirements based on parameter values, component duty cycles, and propellant production capability for the LOX/Si and LOX/Al combinations. Regolith collection/beneficiation mass and power requirements are scaled from values presented in "Conceptual Design of a Lunar Oxygen Pilot Plant" (Eagle Engineering, 1988), which describes a system with a mass of about 3.5 tonnes requiring just over 3 kW of power with the ability to collect over 2.5 tonnes per hour. Because of the uncertainties in beneficiation system design and operational characteristics of excavation machinery in the lunar environment, an additional 50% was added to this system's requirements. Propellant storage systems assume six separate LOX tanks buried in lunar regolith designed for 1 MPa pressure, 5 mm MLI, and a safety factor of 2. The powderized metals to be mixed with the LOX are stored in aluminum spherical storage tanks with 5 mm thickness. Power requirements for propellant storage only account for refrigeration power to reliquefy oxygen. Power system requirements are estimated using the 1985 NASA Space Systems Technology Model reported values for the SP-100 power plant (at a specific mass of 21.19 kg/kWe).

Because the processing schemes studied to date for LOX/CH_4 and LOX/CO use similar approaches, only one set of values was assigned to both. The values of these parameters have been estimated from one source only and cannot be accurately compared to the values given for LOX/Al and LOX/Si. The processing system for these propellant combinations has three separate subsystems: 1) a mobile system that collects lunar regolith, heats the regolith, and collects the evolved gases; 2) a central facility to selectively condense out the gases in the collected gas mixture; and 3) a gas processing facility that optimizes production of methane or carbon monoxide. The plant mass and energy parameter low values shown in Table 3-6 for LOX/CH_4 and LOX/CO represent only the mobile system and central gas condensation facility. The high estimate for feedstock for propellants recovered from solar wind gases doubles the low estimate to reflect the uncertainty in distribution and abundances of these gases in the regolith. In the design presented in the literature a direct solar concentrator was used on the mobile system to provide thermal energy to heat the lunar regolith as it is collected. For sizing the power system to support LOX/CH_4 and LOX/CO production, approximately 30% of the energy required comes from the solar concentrator and is not used to derive surface nuclear power system requirements.

For the LOX/CH_4 and LOX/CO combinations, separate estimates must be made for the additional gas processing systems to utilize collected solar wind gases for optimization of production of either methane or carbon monoxide. For the LOX/CH_4 combination, additional requirements include the ability to heat hydrogen and carbon monoxide gases separated from the solar wind gas mixture to a process temperature of 1200° C for methane and water production, a Sabatier reactor where this reaction occurs, a water electrolysis unit (which was estimated using equations presented in "Conceptual Design of a Lunar Oxygen Pilot Plant"), and both LOX and LCH_4 storage systems designed with similar assumptions to the LOX storage system used for the LOX/metal gel combinations. Power system design also uses the SP-100 values, and does not need to supply power ɔ the mobile system that heats the regolith to extract the implanted volatiles.

TABLE 3-7
PLANT SIZING FOR 1000 T/YR PRODUCTION

Propellant	Mixture Ratio (O/F)	Production System Total Mass (t) Low	Production System Total Mass (t) High	Required Power (MW) Low	Required Power (MW) High
LOX/Si	2.4	125	260	1.5	6.0
LOX/Al	2.3	145	425	1.5	10.7
LOX/CH_4	3.6	250	285	1.0	1.5
LOX/CO	0.6	380	510	3.1	4.1

Although the values assigned to the parameters in Table 3-6 can be argued, the actual values are likely to fall between our high and low estimates. Table 3-7 shows high and low estimates of system mass and power required for the various propellant combinations all sized to 1000 tonnes per year propellant production. These estimates include all systems necessary on the lunar surface to excavate and collect the raw material through surface storage of the final product. The large range shown for LOX/Si and LOX/Al is due to differences among the various processing alternatives.

The large difference in estimates for the LOX/CH_4 and LOX/CO production systems highlights the effects of the propulsion system's mixture ratio on the size of a propellant production operation. Due to the significantly greater abundance of oxygen compared to the fuel source in lunar regolith, the fuel quantities required impact processing requirements. Results of an investigation of the sensitivity of propellant production requirements on propellant mixture ratio are shown in Figure 3-22. These results also suggest a possible benefit of operating the propulsion system at a higher mixture ratio than would be optimal for performance considerations alone to reduce propellant processing requirements.

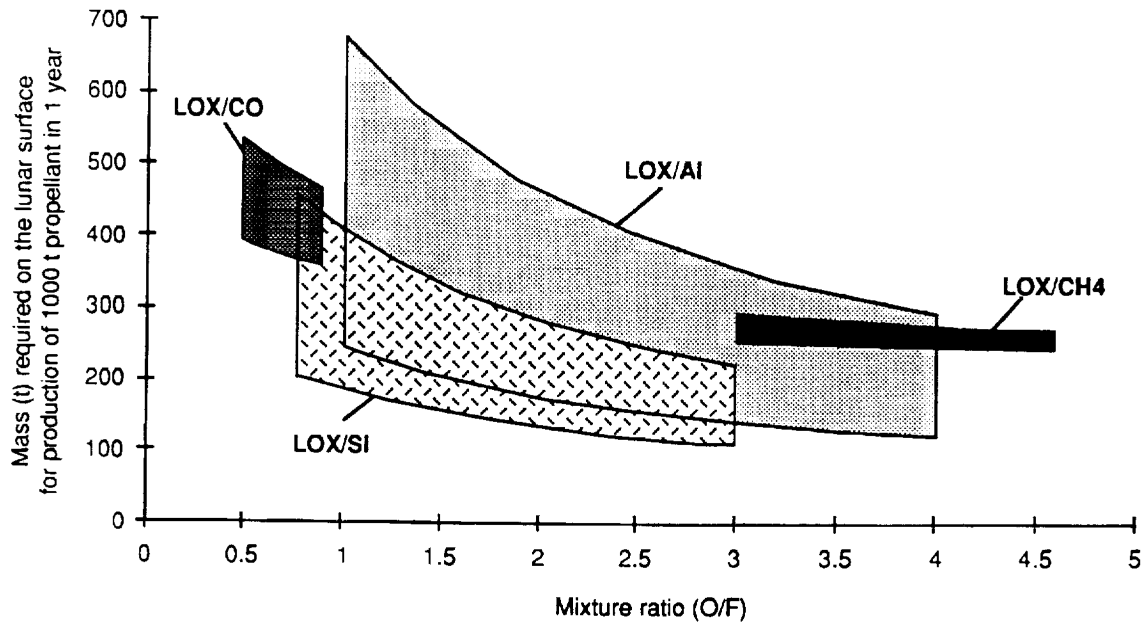


FIGURE 3-22: Effect of Mixture Ratio on Estimated Plant Mass

A mass breakdown for the "low" estimates of production system mass in Table 3-7 is shown as Figure 3-23. The LOX/Al and LOX/Si bars show the relative masses of the following subsystems: collection/beneficiation, processing plant, reagent resupply, power system, and propellant storage. The most significant difference between the two is the greater processing plant mass required for LOX/Al. The requirements for recovering methane and carbon monoxide implanted by the solar wind assume that a mobile miner (Sviatoslavsky and Jacobs, 1988) extracts and stores solar wind gases from processed regolith, which is immediately discarded. The miner then returns filled gas tanks to the central site for separation of the species of interest. Preliminary design estimates indicate that recovery of either LOX/CH_4 or LOX/CO in this manner will require much larger system masses than for metallized monopropellants.

Scalability of Plant Requirements. The estimates of mass and power presented above were derived from studies that were designed for different production capabilities. To normalize these data, the results are expressed in terms of 1000 t propellant per year output because this is near the level of production needed to support lunar and Mars transportation systems. Some of the studies used to define parameter values looked at production levels less than 1000 t per year, and some focused on higher production levels. Terrestrial experience suggests that a plant's efficiency increases with increased production. For this study, the parameter values shown in Table 3-6 are assumed to be applicable for production levels beyond 1000 t per year. This approach seems to penalize the 1000+ t per year propellant production operation, but

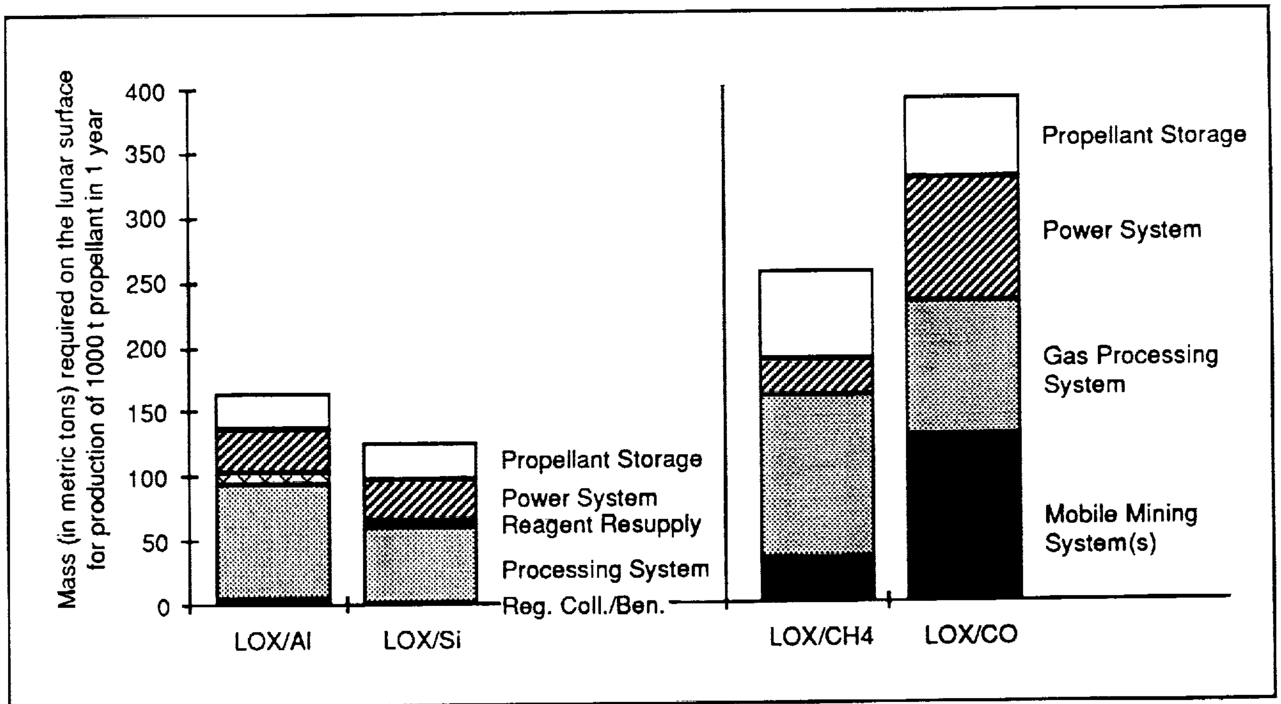


FIGURE 3-23: Subsystem Component Masses by Propellant Manufactured

without more experience on how the various subsystems involved are affected by increasing production levels, the "economy of scale" is difficult to predict. All estimates are based on predicted performance and do not account for lunar environment effects on materials/components lifetimes and processes.

Technology Readiness

NASA's OAET defines seven categories of "readiness" of basic and applied research for space systems, and advanced technology development projects:

Level 1 - Basic principles observed and reported
Level 2 - Technology concept/application formulated
Level 3 - Analytical and experimental critical function and/or characteristic proof-of-concept
Level 4 - Component/breadboard validation in laboratory
Level 5 - Component/breadboard demonstration in relevant environment (ground or space)
Level 6 - System validation/engineering model demonstrated in relevant/simulated environment
Level 7 - System validation/engineering model demonstrated in space environment

None of the candidates presented in this report have been developed beyond technology readiness level 4. Table 3-8 shows an estimated technology readiness level for each process. This estimate emphasizes the point that much more research is needed to assess performance of the many alternatives for lunar propellant production. Although much work has been done at the conceptual level for many of these alternatives, only three candidates, hydrogen reduction (Gibson and Knudsen 1988), carbothermal reduction (Rosenberg 1965), and HF leach (Waldron 1985), have been demonstrated in a laboratory environment. The estimates of technology readiness apply only to the processing system and do not address pre-processing,

TABLE 3-8
ESTIMATES OF TECHNOLOGY READINESS

PROCESS	NASA/OAET READINESS LEVEL
Hydrogen Reduction	4
Carbothermal Reduction	3-4
Hydrogen Sulfide Reduction	1-2
Carbochlorination	2-3
Hydrofluoric Acid Leach	3-4
Reduction by Li or Na	2-3
Reduction by Al	2-3
Direct Fluorination	2
Magma Electrolysis	2-3
Fluxed Electrolysis	2-3
Solar Wind Gas Extraction	2
Vap/Fractional Distillation	2
Selective Ionization	1

or beneficiation, technologies required. Processes requiring isolation of a specific lunar mineral, oxide, or silicate rely heavily on the development of a feasible beneficiation strategy. Some work has been performed for removal of ilmenite from lunar materials (Agosto 1985) but this work did not simulate actual conditions that would be experienced for application in the lunar environment. Other beneficiation schemes have been conceptualized but more research and laboratory experiments are needed.

4. BIPROPELLANTS FROM THE MARS ATMOSPHERE

Likely first candidates for Mars-derived fuels are CO and CH_4, if only because of the ubiquitous CO_2 atmosphere. The C and O components can be readily extracted using relatively simple processing methods. Hydrogen for the methane combination could be brought from Earth, or possibly recovered from martian permafrost in certain locations (more exploratory information is required to confirm this possibility). Expediency might indicate that choosing a bipropellant with a lower specific impulse is a good trade in return for a smaller investment in the surface chemical plant.

4.1 MARS IN SITU ATMOSPHERIC RESOURCES

The atmospheric composition at the surface of Mars was analyzed using the gas chromatograph/mass spectrometers aboard both Viking landers in the mass spectrometry mode (Owen et al. 1977). Readings of atmospheric composition taken at Chryse Planitia by Viking Lander 1 and at Utopia Planitia by Viking Lander 2 are shown in Table 4-1.

TABLE 4-1
ATMOSPHERIC COMPOSITION AT THE MARS SURFACE

GAS	PROPORTION (% or ppm)
CO_2	95.32
N_2	2.70
Ar	1.60
O_2	0.13
CO	0.07
H_2O	0.03 (variable)
Ne	2.8 ppm
Kr	0.3 ppm
Xe	0.08 ppm
O_3	0.03 ppm (variable)

The minute quantities of water that exist in the martian atmosphere rule out its use as a possible source of hydrogen. However, orbital observations by Viking and Mariner spacecraft revealed surface features that suggest the presence of water at or near the surface. If water does exist in the martian regolith, it is probably in the form of permafrost or ground ice. The depth at which such a reservoir might exist depends upon latitude. Near the poles, the ground ice might be within a few centimeters of the surface whereas at the equator, it may be hundreds of meters deep (Farmer and Doms 1979).

Another potential exploitable source of both CO_2 and H_2O are the polar ice caps. The north polar cap is composed primarily of water-ice and varies in size seasonally. The south polar cap is primarily carbon dioxide. The difference in composition between the two poles is temperature dependent. At the north cap, the ambient temperature (205 K) is cold enough for water to precipitate out of the atmosphere as frost, but it is too warm for carbon dioxide frost (Carr et al. 1984). At the south pole, temperatures are around 160 K, cold enough for carbon dioxide frost to exist on the surface (Kieffer and Palluconi 1979).

4.2 PROPELLANT PROCESSING

Because Mars has an atmosphere, strategies for utilization of Mars-based resources for propellant production are very different from most of the strategies proposed for lunar resource utilization. The atmosphere is more than 95% carbon dioxide with 2-3% nitrogen; it has a temperature of about 200 K and an atmospheric pressure of 6-7 mb. Although little is known of soil composition, processing of the atmosphere is very likely to be much less resource-intensive than utilization of resources in the soil. The existence and accessibility of permafrost on the Mars surface would have a significant impact on Mars resource utilization strategies. Since additional data is needed to better assess the feasibility of utilization of Mars surface resources, only processes utilizing atmospheric resources will be considered here.

Two approaches have been proposed for using the Mars atmosphere to recover propellant. The first, presented in 1978 by Ash et al., describes a system that utilizes absorbed water to react with atmospheric carbon dioxide to produce methane and oxygen. Other studies have suggested transporting hydrogen from Earth to react with carbon dioxide from Mars, yielding either methane or hydrogen fuel. The second approach uses oxygen production from carbon dioxide processing, which is utilized in methane production schemes and in many other Mars resource utilization concepts either to obtain enough oxygen to provide adequate mixture ratios for a methane/oxygen or other chemical propulsion systems or for life support purposes. Zubrin et al. (1991) report an interesting variation of LOX/CH_4 utilization.

Production of oxygen from carbon dioxide could also yield carbon monoxide which can be used with the oxygen obtained in a LOX/CO propulsion system. Recent studies by J. French (1989) and D. Galecki (1988) suggest the potential for use of a LOX/CO propulsion system for Earth return transportation from Mars.

Processing Candidates

Both processing candidates discussed previously for Mars propellant production are summarized below. To allow fair comparison of propellant combination accessibility, mixture ratios will be assumed for optimum specific impulse to drive processing requirements. The ratios used to define processing requirements are 3.6 for methane/oxygen and 0.6 for carbon monoxide/oxygen.

Methane/Oxygen Production. Three principal reactions are involved in this process. The first utilizes a Sabatier reactor, which combines carbon dioxide from the Mars atmosphere with hydrogen gas at approximately 370° C over a catalyst to produce methane and water. The water is condensed and electrolyzed to recover a portion of the hydrogen reagent and to obtain oxygen. Additional carbon dioxide must be collected and electrolytically reduced using an 8% yttria-stabilized zirconia solid electrolyte to obtain the required amounts of oxygen to burn with the methane collected in a propulsion system operating at a 3.6 O/F mixture ratio. A flow diagram of the process is shown in Figure 4-1. All the subsystems used in this processing scheme have been tested, although additional study is needed to optimize the zirconia cell separation of oxygen from carbon dioxide. Single pass conversion efficiencies of near 99% can be realized by the Sabatier reactor, but conversion efficiencies in the zirconia cell may be in the 10-30% range.

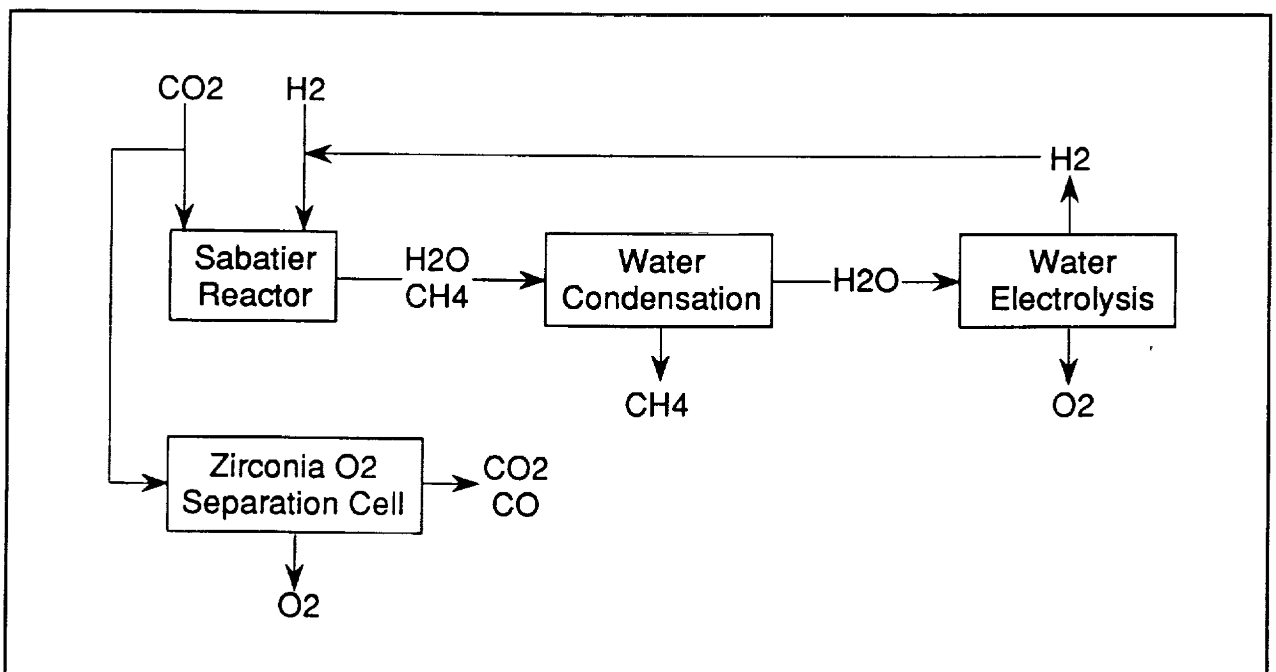


FIGURE 4-1: LOX/CH_4 from Mars Atmosphere

Carbon Monoxide/Oxygen Production. The production of carbon monoxide/oxygen is a subset of the previous processing scheme for methane/oxygen production with additional systems for removal of carbon monoxide from the carbon monoxide/carbon dioxide mixture produced in the zirconia cell. The flow diagram is shown in Figure 4-2. The 110 K difference in boiling points between carbon dioxide (~190 K) and carbon monoxide (~80 K) allows efficient removal of carbon dioxide using a 140-150 K refrigerator system. This additional refrigeration system adds significant mass and energy requirements to this processing scheme.

Process Design

The hardware systems utilized for Mars atmospheric processing are all based on technologies for which significant terrestrial experience exists. The only part of the Mars processing schemes that is not based on decades of experience is the zirconia cell separation of oxygen from carbon dioxide. On Earth, one of the most widely used approaches for obtaining oxygen is to distill it from air using large amounts of refrigeration, but the use of zirconia cells for separation of oxygen from air may allow significant reductions in electrical energy required. For this reason, efforts have been made at JPL (1988) to optimize a zirconia oxygen separation cell design with air feedstock. The current design improves oxygen separation efficiency by about two orders of magnitude.

Requirements for the Mars atmosphere processing alternatives have been derived from several sources. The main reference used here is a presentation by R. Frisbee of JPL made at the third Case for Mars

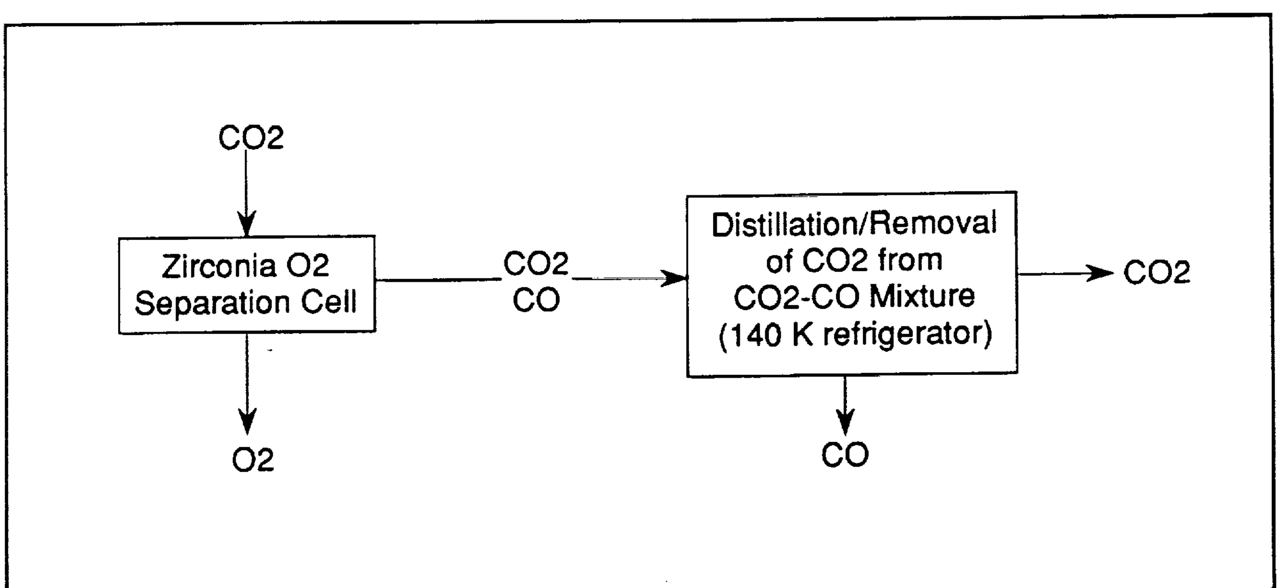


FIGURE 4-2: LOX/CO Production from Mars Atmosphere

Conference (1987). The requirements for the Sabatier reactor have been taken from work on life support systems described by P. Quattrone (1981). Additional requirements have been derived using the 1985 NASA Space Systems Technology Model. Table 4-2 shows the estimated requirements for the methane/oxygen and carbon monoxide/oxygen production alternatives. These requirements include all required subsystems and power sources but do not allow for miscellaneous structure mass.

The reagent resupply requirement for methane/oxygen production assumes all required hydrogen would be supplied from Earth or other non-martian source. This is important to note because it is likely that an evolved martian outpost will develop the means to extract water from permafrost, which can be electrolyzed to supply the required hydrogen to reduce the atmospheric carbon dioxide. This study does not include any estimate of the sizing and requirements to support processing of martian surface water resources; a suitable electrolysis plant and support elements would be added to the emplaced surface components at Mars.

TABLE 4-2
MARS ATMOSPHERE PROCESS CHARACTERISTICS

	LOX/CH_4	LOX/CO
Assumed Propellant Mixture Ratio (O/F)	3.60	0.6
Plant Mass (t per t propellant/yr)	0.07	0.16
Power (kWe per t propellant/yr)	0.60	0.77
Reagent Resupply (t per t propellant)	0.05	0.0

5. MARS TRANSFER MISSION PERFORMANCE

Current planning for SEI recognizes the need to make use of extraterrestrial resources to sustain human presence and to attain some degree of self-sufficiency. As a practical matter, reducing the need to carry large supplies of propellant from Earth will eventually make space exploration more economical. For nearly every round trip planned with conventional propulsion, the real payload is only a small (perhaps 10-15%) fraction of the mass launched from Earth.

Using ISPP to increase payload or lower IMLEO is an approach that piloted missions share with robotic sample returns (Stancati et al. 1979). For a conventional single stack configuration of a complete round-trip vehicle (i.e., excluding split mission designs), propellant for later burns must be carried as "payload" through earlier burns in the mission sequence. The result is almost always a constraint on payloads for both outbound and return legs. This constraint can be relaxed by any of several strategies:

- Minimize ΔV: use minimum energy trajectories, gravity-assist techniques, multi-impulse perigee kick techniques, aerocapture to orbit, or direct atmospheric entry
- Drop masses when no longer needed: use staged tanks or engines, separate excursion and transfer vehicles
- Split Mission Profile: crew and minimal hardware use a fast outbound transfer to rendezvous with larger "tanker" or return vehicle configuration for return trip, and perhaps operational hardware (including the excursion module) at the target
- Decouple propulsion requirements: use ISPP to refuel at Moon, Mars, or both, reducing or eliminating the need to carry propellant before it is needed.

Among these strategies, ISPP is unique; all the others rely on Earth-supplied propellant, varying only the amount that is needed, or how it is delivered. ISPP, with refueling at the target, effectively decouples the outbound and return legs by eliminating the need to bring all propellant from Earth.

This section discusses the performance analysis for various ISPP propellant candidates manufactured on the Moon or Mars, and compares the results to baseline performance with all-chemical propulsion using Earth supplies only. For the results presented here, the MTV is the only transportation element considered for ISPP application. The MEV sizing remains fixed, and is scaled according to conventional LOX/LH propulsion. The MEV and LEV could also use ISPP; these applications are considered in Section 6. The single MTV flight considered is assumed to be "steady-state": that is, occurring after all ISPP plant equipment and infrastructure are in place and operational. The complete infrastructure/architecture assessment presented in Section 6 will include the performance impact of delivering and maintaining plant and equipment.

5.1 ASSUMPTIONS

The performance assessment begins with several assumptions to define a reference profile for a single round trip to Mars. The general requirements, and many of the specific details, are taken directly from analytical work supporting NASA's 90-Day Study. However, the results of the ISPP cases cannot be compared directly with initial masses from the 90-Day Study, since the reference Earth-supplied propellant cases used here assume all-propulsive capture into orbit, rather than aerobraking. (One case with aerobraking is shown for reference; all others assume propulsive orbit capture with chemical propulsion.) Also, ISPP vehicle design concepts have not been examined in any detail. The key assumptions are presented below for round trips to both Mars and to the Moon, the latter since lunar resources are critical to many of the utilization scenarios.

Crew Size, Vehicles, and Payloads. The Transfer and Excursion Vehicles for Moon and Mars support a crew of four. Preliminary design work sized both Mars vehicles (MTV and MEV) for an opposition-class, short stay time round trip flight profile. Vehicle design accounts for propellant loading, radiation shielding, and consumable supplies for the round trip. Consumables (food, water, oxygen, etc.) are estimated at 93 kg per crew member per month, or about 5,500 kg for the reference Mars profile (described later). The LTV also carries radiation shielding and provisions, but sized for the shorter trip times.

For lunar transfer, the mass of the LTV inerts and crew module is 16.5 metric tons (t); propellant loading and tanks are added to this mass, according to the requirements of each selected propellant. The corresponding LEV mass is 10.2 t. The LEV can deliver approximately 27 t of cargo (or a 13-15 t cargo and one crew with habitation module) to the lunar surface, assuming that the LEV is to be reused. The Mars transportation system supports a crew of four; in addition, it is sized to deliver a 25 t payload to the Mars surface, and to return a 1 t payload to Earth. The MTV mass at Earth return is 30 t. The MEV delivered to Mars orbit weighs 75 t.

Orbit Selections. Earth orbit operations for all cases considered in this study assume departure from a circular orbit at 407 km altitude: i.e., the Space Station Freedom orbit. Returning transfer vehicles capture into a 500 km by 24 hour orbit at Earth. Impulses are calculated for injection burns to and from these orbits. A circular low lunar orbit (LLO) at 300 km is used for vehicle rendezvous, propellant transfer operations, etc. The Mars orbit for capture, rendezvous, and departure is elliptical, with a period of 1 sol (martian day: 24.6 hours) and periapse altitude of 250 km above the planet's surface.

Interplanetary Trajectory. A single reference trajectory is used for all Earth-Mars round trip performance calculations discussed in this section. Figure 5-1 shows the heliocentric profile and details of the major impulses. The reference trajectory (as identified and presented by Boeing, Huntsville, AL) is for the 2016 opposition-class opportunity; key characteristics include a 30-day stay time at Mars, and a Venus gravity-assisted swingby on the return leg. In most respects, the 2016 trajectory is typical of opposition-class round trips. However, the 434 day total round trip is unusually fast; other opportunities searched by SAIC require at least 500 days, and as much as 640 days in a few cases, to reach approximately the same total impulse budget as shown in Figure 5-1. Note also that the departure burns are increased to account for various non-ideal conditions: Earth launch window and finite-burn gravity losses, plane change maneuvers to meet the departure asymptotes, and an allowance to rotate the Mars orbit apseline.

Propellant Characteristics for Performance Evaluation. Table 5-1 summarizes essential defining quantities for each monopropellant and bipropellant considered in this study. Performance numbers are taken from data supplied by D. Linne of NASA/LeRC. Mixture ratios were selected to give optimum specific impulse for an engine operating at a chamber pressure of 200 psia, and a nozzle expansion factor of 200. Propellant densities and a hydrogen boiloff rates were used to size propellant tanks and insulation needs. For the short Earth-Moon transfer, 3.27 kg/month/square meter of tank surface area was selected to represent hydrogen

TABLE 5-1
PROPELLANT CHARACTERISTICS

Propellant (Constituent)	Vac Isp (Sec)	Mixture Ratio	Density (kg/m^3)
LOX/ LH_2	475	6:1	1140 71.2
LOX/Al	296	2.3	1382
LOX/Al-Mg	295	1.9	1409
LOX/Fe	195	1.6	1699
LOX/Si	288	2.4	1342
LOX/Ti	267	1.6	1600
LOX/ CO	298	0.6	1140 790
LOX/ CH_4	392	3.6	1140 415

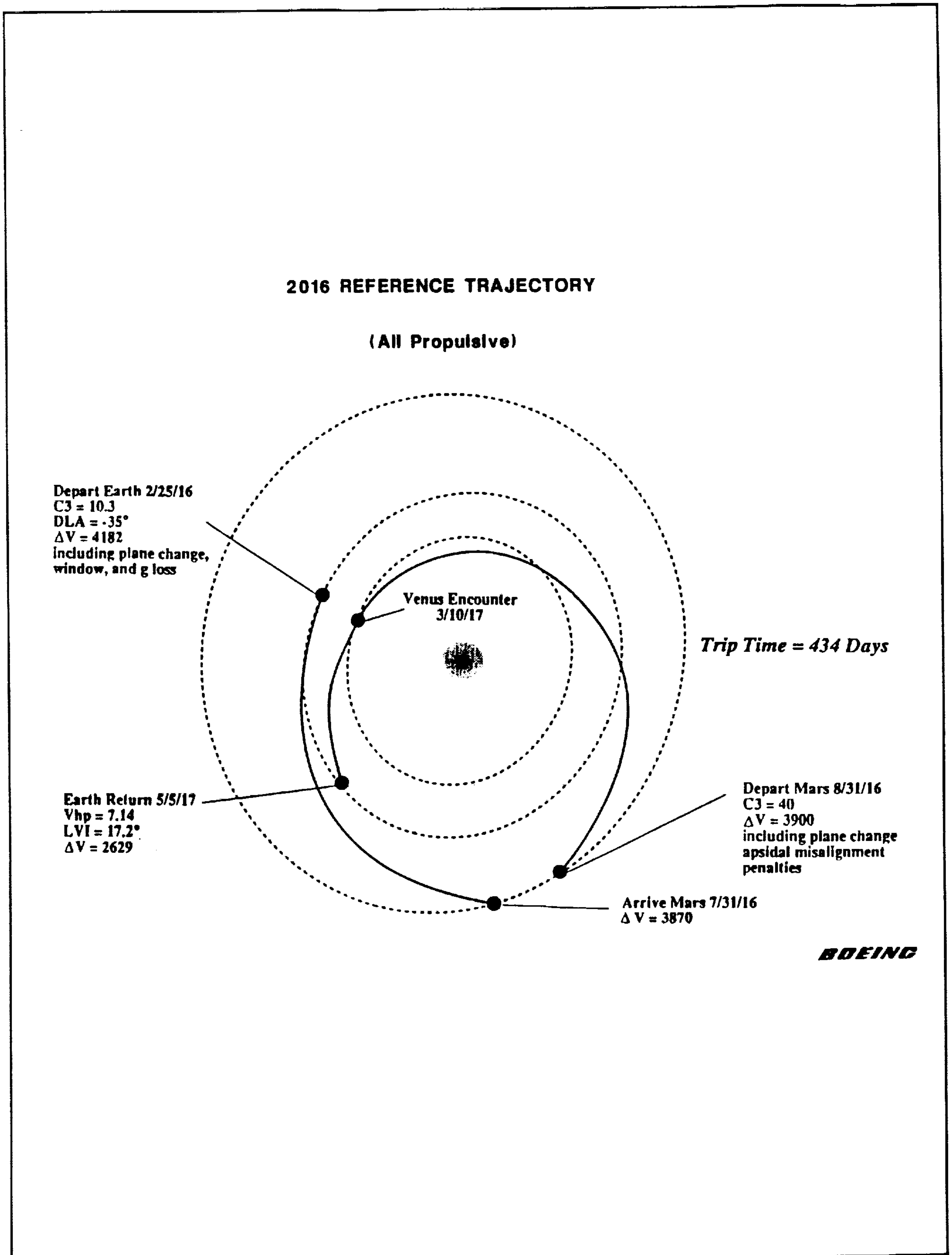


FIGURE 5-1: 2016 Reference Trajectory (after Boeing)

boiloff with minimal insulation. Other tanks were designed for a boiloff value of 0.818 kg/month/m^2. Boiloff was assumed to be negligible for other propellant constituents.

Propulsion Inert Mass Scaling. Tank mass is calculated from required propellant mass (plus a reserve of 2% of requirement) using mass scaling factors of 12% for hydrogen fuel mass, and 2% for all other constituents. Additional allowances include tank set structure, at 10% of total dry mass, and multi-layer insulation at 2 cm thickness for Earth departure tanks, and 8 cm for all other tanks. Tank volume assumes cylindrical tanks with (Root2/2) ellipsoidal end caps. For this study, all staged tank masses are assumed to be "rubber": they are sized exactly to propellant requirements. A vehicle design concept study would pick a fixed size (or possibly two) and take the mass penalty associated. However, for this preliminary study, faster calculations are possible using the rubber sizing. This assumption is typical of trade studies, and is a reasonable first estimate, so long as the propulsion options being considered are of roughly the same density and mixture ratio.

5.2 MARS MISSION PROFILES

Four basic profiles, or utilization strategies, may be considered for propellant manufacturing at Mars, on the Moon, or both, to support an Earth-Mars round trip. Figure 5-2 gives a schematic summary of each of the four.

Profile (a): Baseline Chemical and Mars ISPP. The baseline MTV flight calls for assembly and departure from a LEO node (here assumed to be Space Station Freedom). Empty tanks are jettisoned after trans-Mars injection. The MTV delivers its cargo, the MEV, to a 250 km by 1 sol orbit at Mars using chemical retro-propulsion, from which the MEV later brakes and descends to begin the surface mission. After rendezvous in orbit with the ascent configuration of the excursion vehicle, the MTV departs on the return to Earth, capturing into a 500 km by 24 hour orbit. (Refer to Figure 5-1 for more detail on trajectory events.) The ISPP options considered for this scenario include Mars-produced LOX/CO and LOX/CH_4 and Mars LOX combined with Earth LH_2 for the return leg; outbound propulsion for all these cases is Earth-supplied LOX/H_2.

Profile (b): MTV 3-Leg Using LEO and LLO. Several alternative utilization scenarios may be considered for lunar-supplied ISPP assessment. The approach shown in Figure 5-2(b) uses an expendable LOX/LH_2 stage to move the assembled MTV to LLO, where it is fueled for the round trip to Mars. The MTV returns to the LEO transportation node to deliver the crew and for refurbishment. The interplanetary trajectory is unchanged in most details; the only required modification is leaving LLO for an Earth swingby to injection on the outbound trip. The MTV would continue in this manner for the rest of its operating lifetime, supported

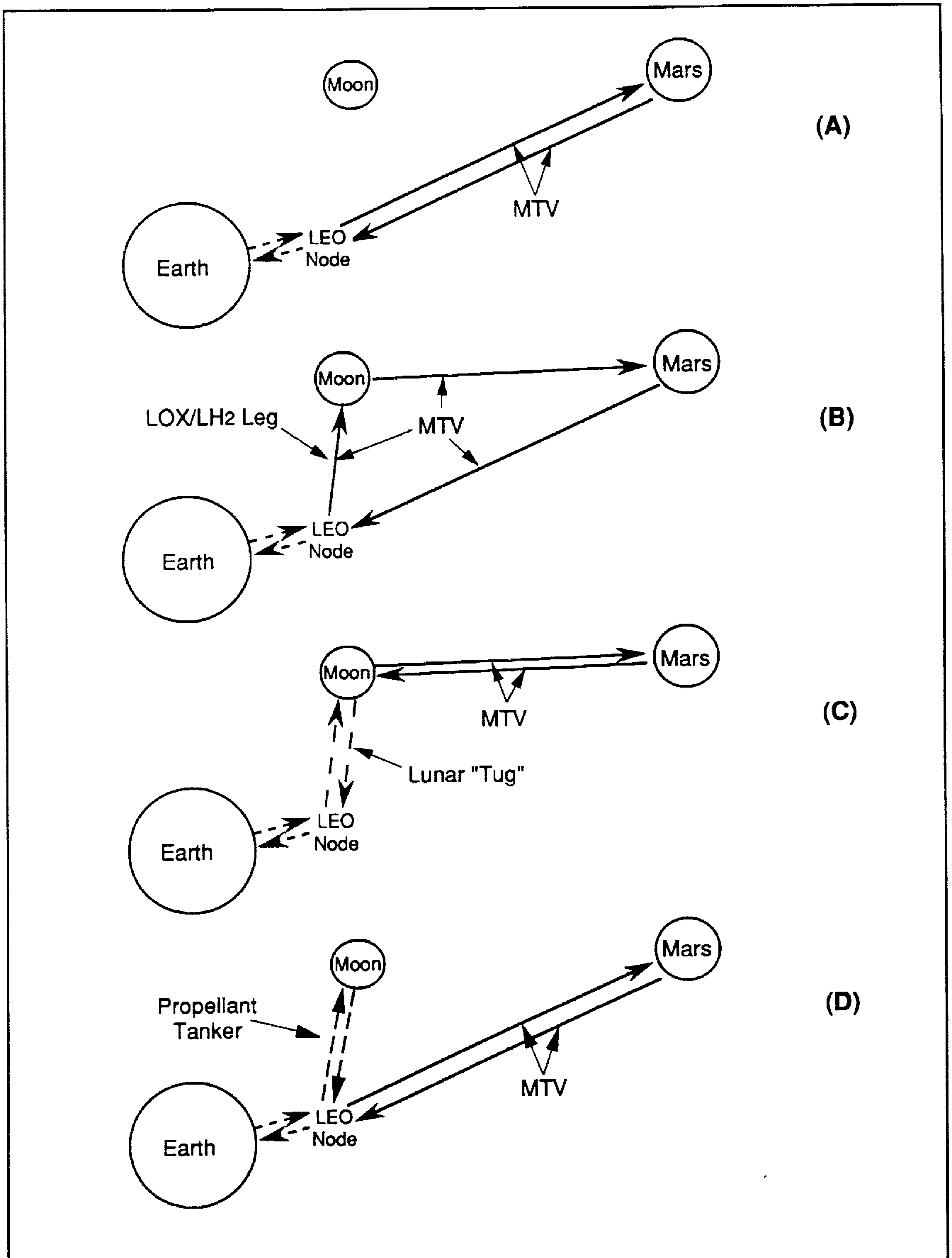


FIGURE 5-2: ISPP Utilization Strategies

from a LEO node, but fueled for the interplanetary trips in lunar or Mars orbit, or perhaps at both locations. Although the MTV handles all three legs, it does require added propulsion for the trip to the Moon, which we have assumed to be handled by an expendable LOX/LH stage or tank set.

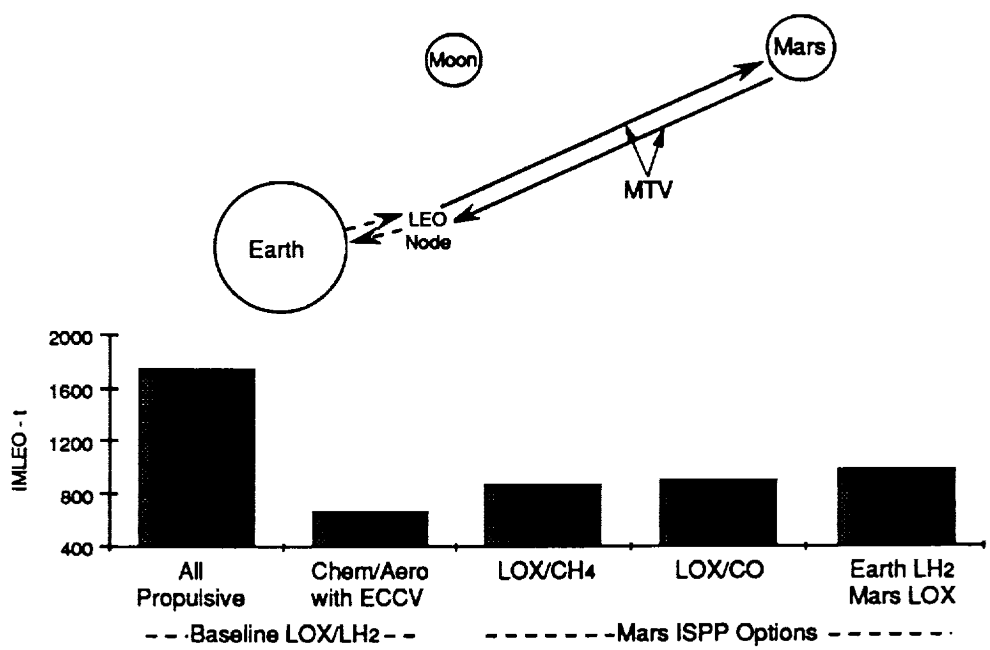
Profile (c): MTV Operates from LLO Node. Another strategy for using lunar-derived propellant is to base the MTV at a transportation node in LLO, leaving and returning from that point, and employing a combination of lunar shuttles or "tugs" to move crews and payloads between LEO and LLO. As for case (b), the MTV leaves LLO, executes a perigee kick, and departs for Mars. On return to Earth vicinity, the MTV executes a three-impulse capture sequence to a 300 km circular orbit about the Moon. (This requires an additional 300-400 m/s over capture to the reference Earth return orbit.) This approach effectively bases the MTV in LLO; a second in-space transportation node would probably be required there to support crew and payload transfers from shuttles, and propellant from the Moon to the MTV configuration.

Profile (d): MTV and Lunar Tanker Operate from LEO Node. A commonly discussed IMLEO reduction approach using lunar ISPP would ferry the propellant supply from the Moon back to the transportation node in LEO. As in the baseline case, the MTV departs from and returns to LEO. In all other respects, this case is the same as case (a). This use of ISPP requires a propellant tanker, perhaps a modified version of the LTV, to deliver empty tanks to the Moon and return with propellant loads for the Earth-Mars trip.

5.3 SINGLE-MISSION PERFORMANCE COMPARISONS

The following figures summarize the single-mission performance analysis results for the MTV for each of the four utilization scenarios described. Some ISPP propellant candidates are eliminated from further consideration, as will be discussed.

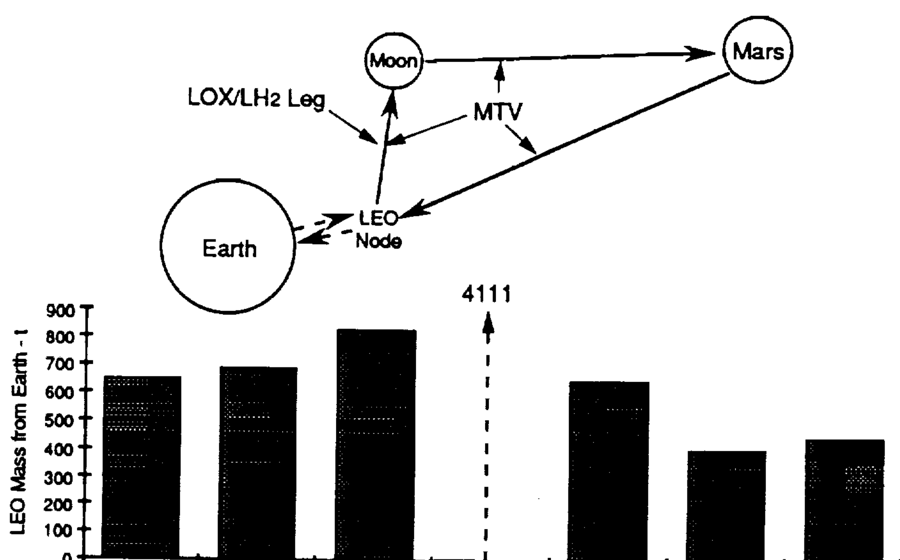
Profile (a): Baseline Chemical and Mars ISPP. With an Earth-derived all-propulsive approach, 1746 t must be delivered to LEO; this assumes that the entire MTV is returned to Earth orbit. The reference mission design uses two techniques -- a Mars aerobrake to reduce the capture impulse, and direct entry at Earth return of an Earth Crew Capture Vehicle (ECCV) -- to reduce the IMLEO requirement to 666 t. However, only the ECCV returns; the rest of the MTV is expended. The three bars for ISPP options (Figure 5-3) assume all-propulsive flight, with no aerobraking or ECCV direct entry on return. As with the all-propulsive baseline, all of these return the MTV to LEO where it could be refurbished. IMLEO masses for these three options are comparable, with Mars LOX/Earth LH_2 being heaviest, since the outbound leg carries hydrogen fuel for the return. However, the Mars production requirements differ substantially, depending on specific impulse of the particular bipropellant. The LOX/CH_4 mass would be reduced if methane could be made with hydrogen from Mars; we assume the hydrogen is carried from Earth. Recall that no allowance is made here for deploying or supporting the ISPP plant; that issue will be treated in Section 6.



	All Propulsive	Chem/Aero with ECCV	LOX/CH4	LOX/CO	Earth LH2 Mars LOX
Mass Summary (t)					
LEO Mass from Earth	1746	666	861	895	976
Lunar Production	--	--	191	386	114
Mars Production					
Mass Breakdown (t):					
- Mars mission pyld.	25	25	25	25	25
- MEV	50	59	50	50	50
- MTV:					
core	42	47	42	42	42
drop tanks	74	64	45	51	48
prop. from Moon					
prop. from Mars			191	386	114
prop. from Earth	1555	471	699	727	811

FIGURE 5-3: Baseline Chemical and Mars ISPP

Profile (b): MTV 3-Leg Using LEO and LLO. Figure 5-4 shows the requirements for mass in LEO delivered from Earth for several candidate propellant combinations. For example, a 647 t MTV would leave LEO for LLO, where it would take on 4346 t of LOX/Al propellant. Note that the 647 t includes the LOX/LH_2 stage for the LEO-to-LLO leg. Differences among the set of lunar LOX/metal propellants are readily apparent. LEO masses from Earth for LOX/Al and LOX/Si are comparable, with the higher LOX/Si requirement for tankage and structure to handle an additional 591 t of propellant. The LOX/Ti masses are higher because of the reduced specific impulse. Similarly, LOX/Fe, with Isp = 195 s, gives masses too large to be practical; LOX/Fe is eliminated from further consideration in this study. LOX/Al-Mg performance is almost equal to LOX/Al. The last two bars on Figure 5-4 consider LOX/CH_4 and LOX/CO production at <u>both</u> the Moon for the outbound leg, and at Mars for the return leg. Both of these options show significant reductions in production requirements, since propellant for the return leg is not carried outbound.

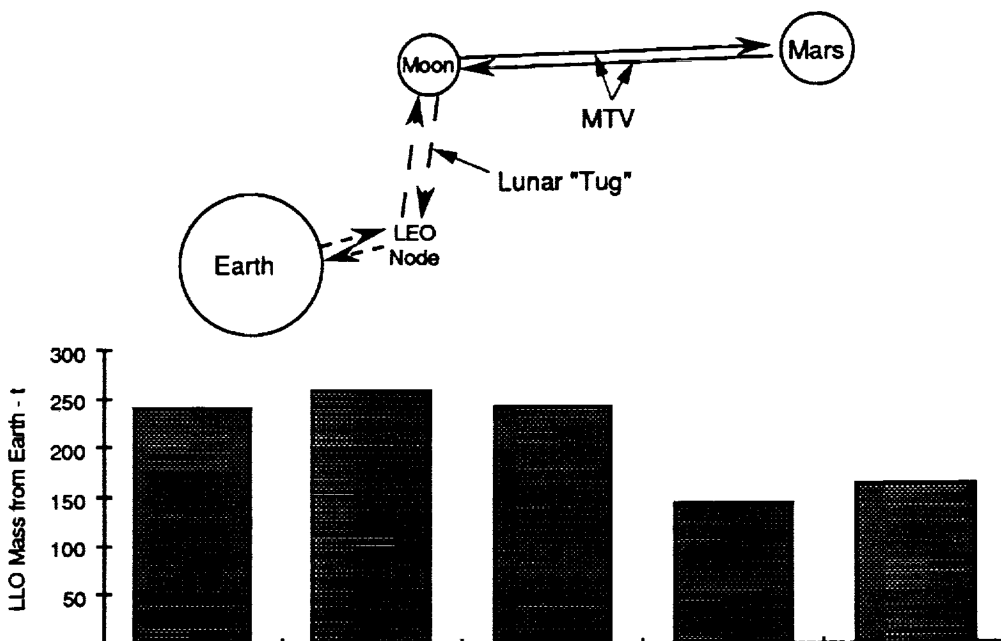


LEO->Mars->LEO	LOX/Al	LOX/Si	LOX/Ti	LOX/Fe	LOX/Al-Mg	LOX/CH4 *	LOX/CO *
<u>Mass Summary (t)</u>							
LEO Mass from Earth	647	689	827	4111	650	404	448
Lunar Production	4346	4937	7230	58594	4399	460	906
Mars Production	--	--	--	--	--	210	425
Mass Breakdown (t):							
- Mars mission pyld.	25	25	25	25	25	25	25
- MEV	50	50	50	50	50	50	50
- MTV:							
core	42	42	42	44	42	42	42
drop tanks	104	119	168	1341	105	17	33
prop. from Moon	4346	4937	7230	58594	4399	460	906
prop. from Mars						210	425
- Expendable Stage							
dry	26	27	31	111	26	20	21
prop. from Earth	400	426	511	2540	402	250	277

* Both Lunar & Mars ISPP

FIGURE 5-4: MTV 3-Leg Using LEO and LLO

Profile (c): MTV Operates from LLO Node. Five ISPP options are considered using this strategy (Figure 5-5). All three of the LOX/metal options will require approximately 250 t of mass launched from Earth and delivered to LLO. Note that these cases cannot be compared directly with the previous ones, since the reported mass is **mass in LLO**, which excludes LEO-to-LLO transportation. Production requirements for the lunar/Mars options are again lower, since the outbound and return leg propellant loadings are decoupled. The higher LOX/CH_4 Isp also reduces the LLO mass from Earth for this case.

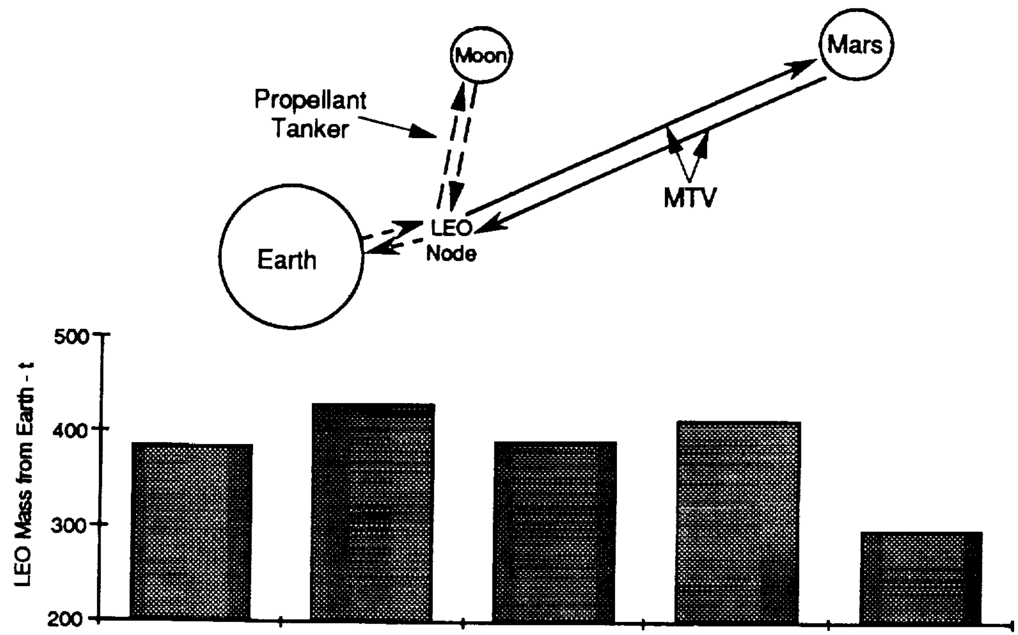


LLO->Mars->LLO	LOX/Al	LOX/Si	LOX/Al-Mg	LOX/CH4 *	LOX/CO *
Mass Summary (t)					
LEO Mass from Earth	241	259	243	145	162
Lunar Production	4946	5644	5009	469	924
Mars Production	--	--	--	238	494
Mass Breakdown (t):					
- Mars mission pyld.	25	25	25	25	25
- MEV	50	50	50	50	50
- MTV:					
core	43	43	43	42	43
drop tanks	123	141	125	28	44
prop. from Moon	4946	5644	5009	469	924
prop. from Mars				238	494
prop. from Earth					

* Both Lunar & Mars ISPP

FIGURE 5-5: MTV Operates from LLO Node

Profile (d): MTV and Lunar Tanker Operate from LEO Node. Figure 5-6 shows the LEO mass that must be delivered from Earth for each of five production options. For example, a 385 t MTV would be fueled with 11,365 t of LOX/Al lunar propellant for the round trip to Mars. Although this utilization strategy improves all-propulsive performance of a single MTV flight, the production requirements for lunar LOX/metal combinations are higher than for the alternative strategies presented above. Moreover, transportation infrastructure to support this approach will include a propellant tanker to move lunar-derived propellant from the Moon to the LEO node.



LEO->Mars->LEO	LOX/Al	LOX/Si	LOX/Al-Mg	Earth LH_2 Lunar LOX	Earth LH_2 Lunar/Mars LOX
Mass Summary (t)					
LEO Mass from Earth	386	430	390	413	297
Lunar Production	11365	13275	11536	1333	679
Mars Production	--	--	--	--	114
Mass Breakdown (t):					
- Mars mission pyld.	25	25	25	25	25
- MEV	50	50	50	50	50
- MTV:					
core	42	42	42	42	42
drop tanks	269	313	272	74	48
prop. from Moon	11365	13275	11536	1333	679
prop. from Mars					114
prop. from Earth				222	132

* Both Lunar & Mars ISPP

FIGURE 5-6: MTV and Lunar Tanker Operate from LEO Node

Several of the candidate propellants show performance that is sensitive to area ratio. Since the results presented so far assume a fixed area ratio of 200, Figure 5-7 explores mass variation as a function of area ratio from 10 to 500 for the three candidates that show the greatest variability in specific impulse with area ratio. This performance trade assumes departure from LLO and return to LEO -- Mission Profile (b). The results indicate that, although larger nozzles produce the expected mass saving in each case, area ratios above 200 show limited performance improvement. For LOX/CO and LOX/CH_4, area ratios of 100 or less

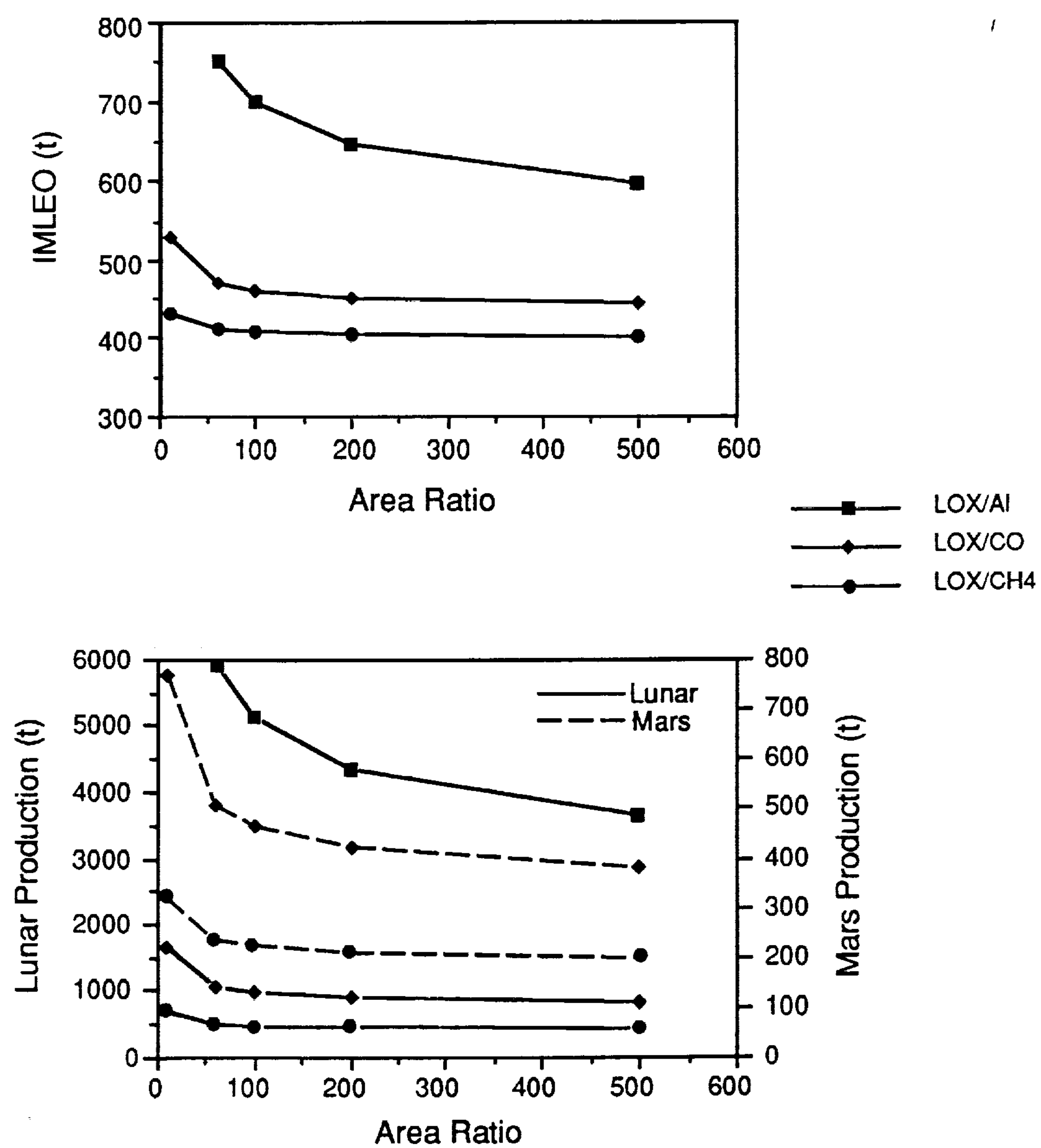


FIGURE 5-7: Sensitivity to Nozzle Area Ratio

produce only small IMLEO penalties. However, the LOX/Al combination is more sensitive to the effect; as area ratio increases from 100 to 500, IMLEO mass declines by about 100 t.

Of the candidate propellants, LOX/Si appears most sensitive to chamber pressure, which was fixed at 200 psia for the results presented so far. For a chamber pressure of 3000 psia, Isp = 297.7 s for LOX/Si, an increase of about 10 s. This improvement (with area ratio held at 200) results in a reduction of about 80 t of mass from Earth delivered to LEO, and a savings of nearly 1200 t in lunar-derived propellant.

6. INFRASTRUCTURE REQUIREMENTS AND ASSESSMENT

A complete assessment of utilization of lunar- or Mars-produced propellants for Mars missions must include the systems needed to manufacture propellant, sustain the manufacturing operation, and deliver these propellants from their point of origin to the point of application. In addition to these systems, maintaining the propellant plant operation will require continuous support. The effects of these requirements on the potential benefits offered by lunar/Mars propellant production can significantly offset the performance gains of using ISPP. In this section, the infrastructure elements considered in this study are identified, the assessment approach and assumptions made are defined, and the results of the assessment are presented.

6.1 INFRASTRUCTURE REQUIREMENTS

Because of limited understanding of operational requirements for a space-based propellant production facility, infrastructure requirements are difficult to define. Figure 6-1 shows some of the elements that could be included in an assessment of infrastructure requirements. The study considered the minimum set of infrastructure requirements for ISPP use that would have a first-order impact on mass performance. The shaded areas in Figure 6-1 represent the elements considered for this assessment.

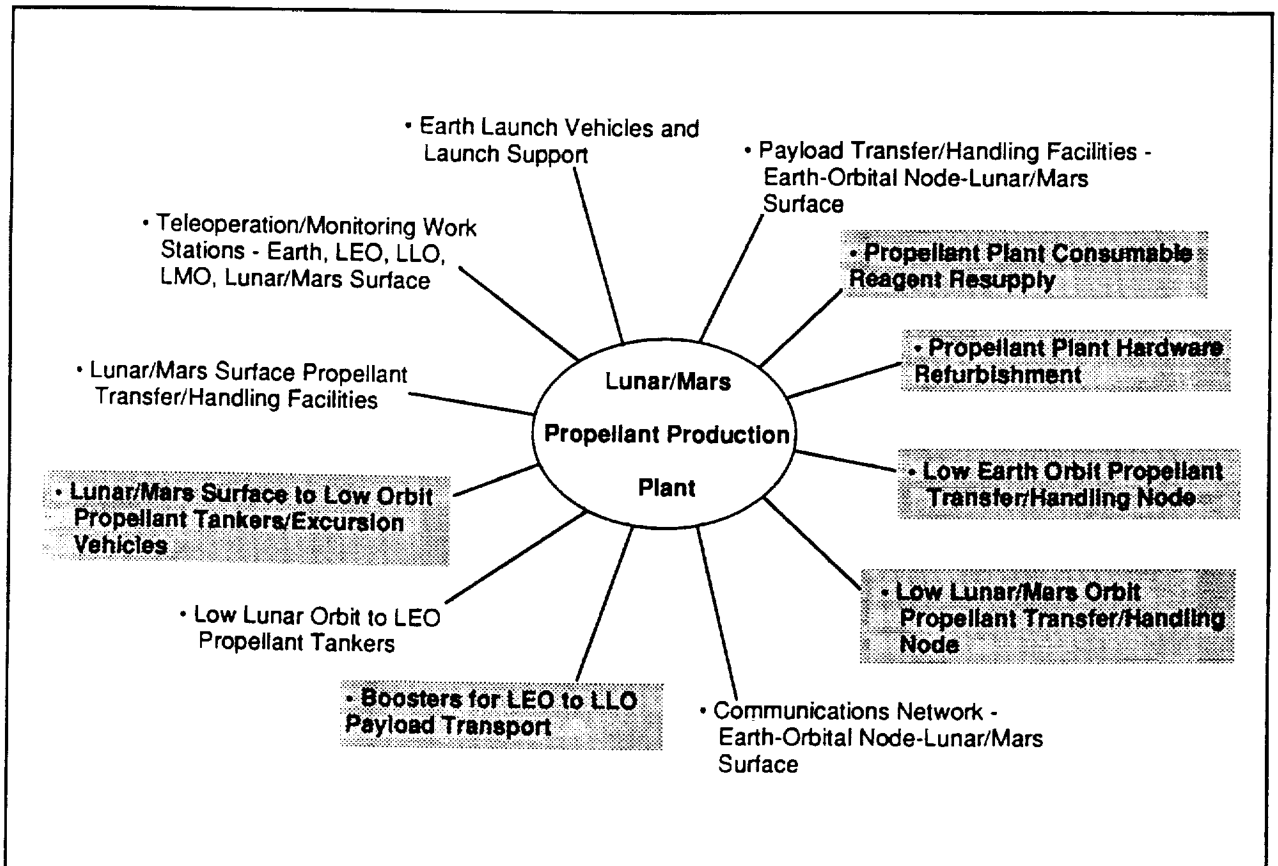


FIGURE 6-1: Key Infrastructure and Support Systems

We assumed that orbital propellant transfer/handling nodes would only be points of rendezvous where propellant is transferred from one vehicle to another. No estimates of orbital facilities are included; this issue should be examined in much greater detail, especially for cases that call for the MTV to depart from low lunar orbit. To do so will require more mission architecture detail and understanding of process requirements than is available in the scope of this study. The masses estimated for the infrastructure elements account for transfer and excursion vehicles, any dropped tanks or stages, propellant plant hardware refurbishment and consumable reagent resupply, and Earth-based propellant and tankage where applicable.

Including infrastructure elements not addressed in this study would certainly affect the assessment of ISPP benefits for a Mars mission; however, the simplified approach does allow equitable comparison of the various strategies for using ISPP propellants. The infrastructure elements included in this assessment could be sufficient for propellant plant support if a high degree of automation is assumed, although this level of automation has yet to be demonstrated for space operations. Also, estimated requirements only account for mass and power needs of a propellant utilization strategy. Estimates of support equipment volumes, which would impact requirements for launch vehicle shroud dimensions and sizing of the space transfer/excursion vehicles, have not been made. Finally, no manpower requirements for operations, maintenance, and refurbishment have been included in this assessment.

6.2 ASSESSMENT APPROACH

The approach used to assess potential benefits from lunar/Mars propellant utilization for Mars missions is illustrated in Figure 6-2. Analysis begins with the selection of a mission payload mass and a destination for the payload, either the lunar or Mars surface. Propellant plant requirements are estimated from a set of parameters specific to the propellant combination under investigation, not to a specific processing system (see Sections 3 and 4). The plant requirements are determined by the propellant production rate which is determined by the transfer and excursion vehicle propellant requirements which is in turn dependent on mission payload mass requirements. After iterating to determine plant resupply mass, requirements for the steady-state operation are obtained. The steady-state requirements assume that the propellant plant(s) have been emplaced along with the required infrastructure elements on prior missions; compared to the results presented in Section 5, steady-state masses include, besides the same mission payloads, plant refurbishment and resupply mass allocations. However, the requirements to establish the propellant plant operation and infrastructure must also be included in the assessment; they will influence when the break-even point occurs with respect to Earth-delivered mass.

Throughout the analysis, Earth-delivered mass is used to represent the requirements of a given scenario. IMLEO, commonly used for performance assessments and as a proxy for cost, is not strictly applicable for

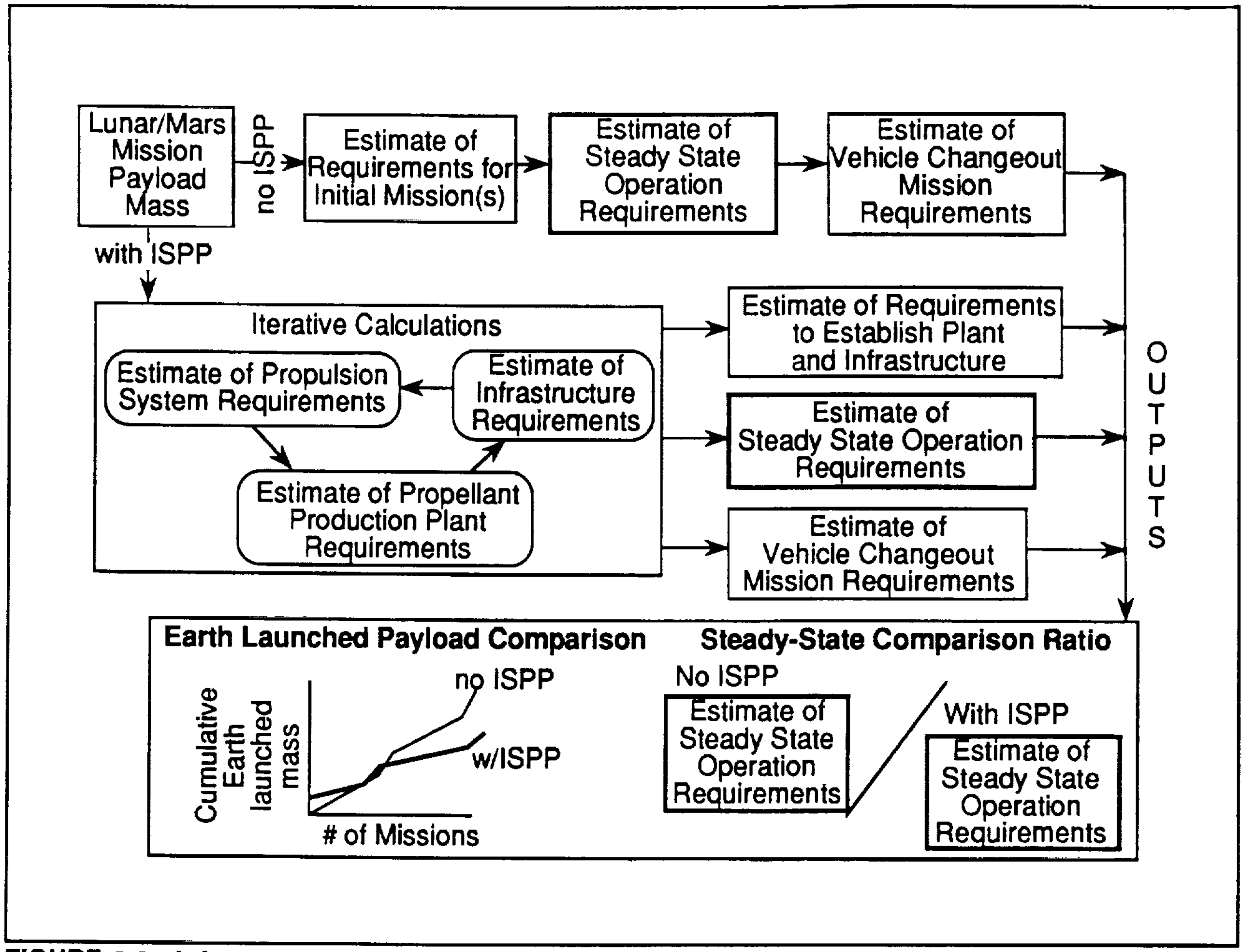


FIGURE 6-2: Infrastructure Assessment Approach

the purposes of this study. The reason is that not all the mass leaving LEO (or an alternate LLO staging point) for a given mission need be launched from Earth. Earth-delivered mass can be less than IMLEO, since transfer or excursion vehicles launched on a previous mission can be reused, and since not all propellant comes from Earth. Because the rationale for producing lunar or Mars propellant is to reduce Earth launch support, Earth-delivered mass is a better indicator of the requirements for an in situ propellant utilization strategy.

Requirements must also be estimated for cases in which the transfer and excursion vehicles are at the end of their life cycles and need replacement. These vehicle change-out mission requirements penalize the scenarios using in situ propellant as well as the scenario using all propellant brought from Earth; however, the mass penalties for the cases using lunar/Mars propellant are typically much higher than for the cases that use only Earth-sourced propellant because the reusable configurations are more massive. The assessment is therefore sensitive to the life cycle of the vehicles used. Consistent with the NASA 90-Day Study, a vehicle lifetime of five round trips was assumed. This estimate is conservative with respect to experience with space hardware, and should probably be examined further. A longer life time (more reuses) would increase the attractiveness of using in situ propellants.

Three parameters characterize each scenario. The first is a ratio of Earth-delivered masses: baseline propulsion without ISPP versus the mass with ISPP. This ratio characterizes the "steady-state" mode of operation; it includes mission payloads, refurbishment missions, and resupply, but it excludes emplacement and change-out needs. So, although this value provides a useful figure of merit for comparison of the alternatives, it does not tell the entire story of overall requirements. The second result is the requirements for establishment of the propellant plant operation. Third, the cumulative Earth-delivered mass savings (comparing a case using in situ propellants to the same case using all Earth-sourced propellants) over several missions is a valuable figure of merit for the actual benefit achievable through utilization of lunar/Mars propellants. This benefit, expressed as a savings in the mass needed to be launched from the surface of Earth, could be translated to a rough estimate of launch cost reduction with ISPP; the cost saving could then be compared to expected development cost of an ISPP system. It is important to consider all three measures to have a clear picture of what is required to establish and support a lunar/Mars propellant plant, and to understand what benefits could be realized. This approach enables investigation of many trades relating to the propellant plant characteristics, space transfer and excursion vehicle design, and Mars mission design.

To gain preliminary insight into how the plant characteristics might affect the vehicle mass performance, several sample cases were assessed using lunar propellant in one LEV for lunar ascent/descent. This preliminary assessment was performed for a lunar mission rather than a Mars mission to reduce the number of infrastructure elements involved, and to focus on issues related to the lunar propellant plant operation. As discussed in Section 3, much uncertainty exists in the estimates for the lunar plant requirements. Figure 6-3 shows a comparison of the ratio of Earth-launched payload using Earth LOX/H2 in the LTV and LEV to using lunar LOX/Al in the LEV for support of a lunar mission with a 27 t payload. The lunar propellant plant parameters investigated include:

- using a power source with a specific power of 12 kg/kWe compared to 21 kg/kWe (the baseline case)
- performing the mission using a smaller (20 t) or a larger (40 t) mission-specific payload
- operating the mining equipment at a 95% duty cycle compared to the baseline value of 25%
- using the "high" values of the parameters from Table 3-5 instead of the reference low values

Figure 6-3 shows the ratio of Earth-launched mass required without lunar propellant to mass required with lunar propellant for each case; the higher the ratio value, the better the performance of ISPP as compared to using Earth-supplied propellants. Note that this characterization is for steady-state operation; it does not account for the initial set-up of the propellant plant, or for delivery of supplies or replacement equipment.

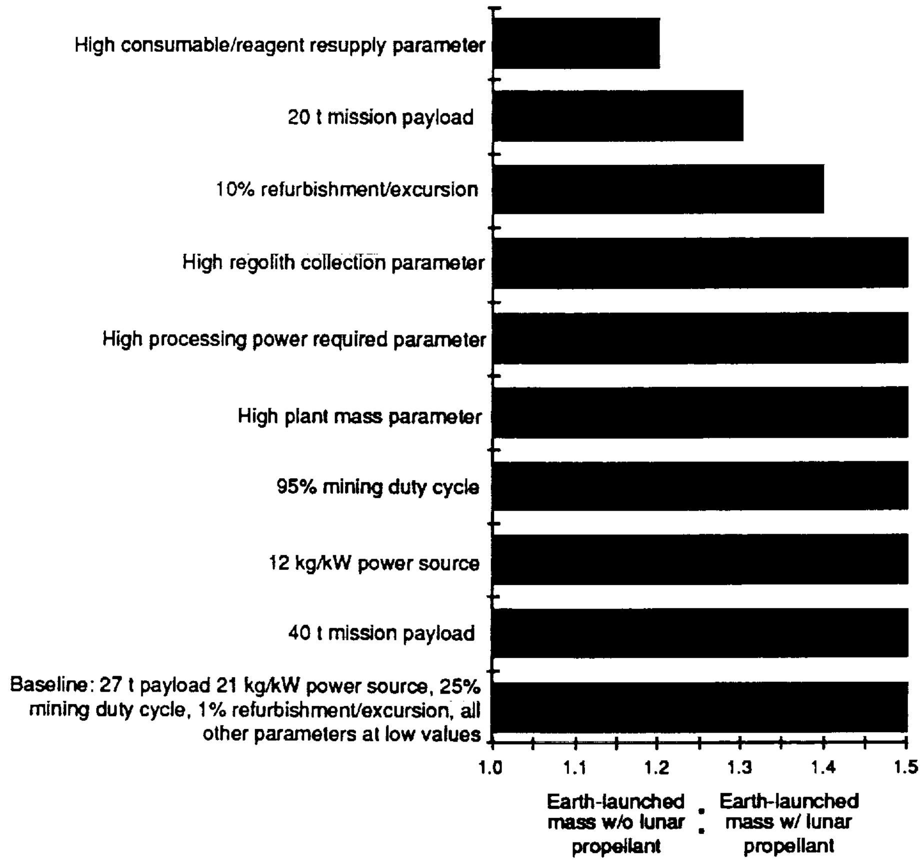


Figure 6-3: Steady-State Mass Comparison for LEV Lunar LOX/Al

The variables that had the greatest effect are the rate of consumable/reagent resupply, the assumed mission payload size, and the hardware refurbishment factor. The performance of ISPP using a smaller mission payload is better than not using ISPP, but the gain is smaller because the application is less efficient than using the larger payload. Resupply and refurbishment rates are also important determinants of potential Earth-launched mass savings. This emphasizes the importance of improved understanding of these requirements.

In all the cases shown in Figure 6-3, operating the LEV with lunar propellant shows a benefit over using LOX/H2 from Earth in "steady-state" mode. But assessments of steady-state operation do not account for the up-front investment required to deliver the plant, or the on-going supply and maintenance. Figure 6-4 shows the cumulative Earth-launched mass savings possible with lunar LOX/Al for the LEV as compared to using LOX/H2 transported from Earth. This savings is based on requirements to set up the lunar propellant plant and to perform 11 lunar missions. Eleven missions represents two full transfer/excursion vehicle life cycles (5 uses per vehicle before replacement). Although most cases appear to have a comparable Earth-launched payload savings to the baseline case, the case which used the high reagent

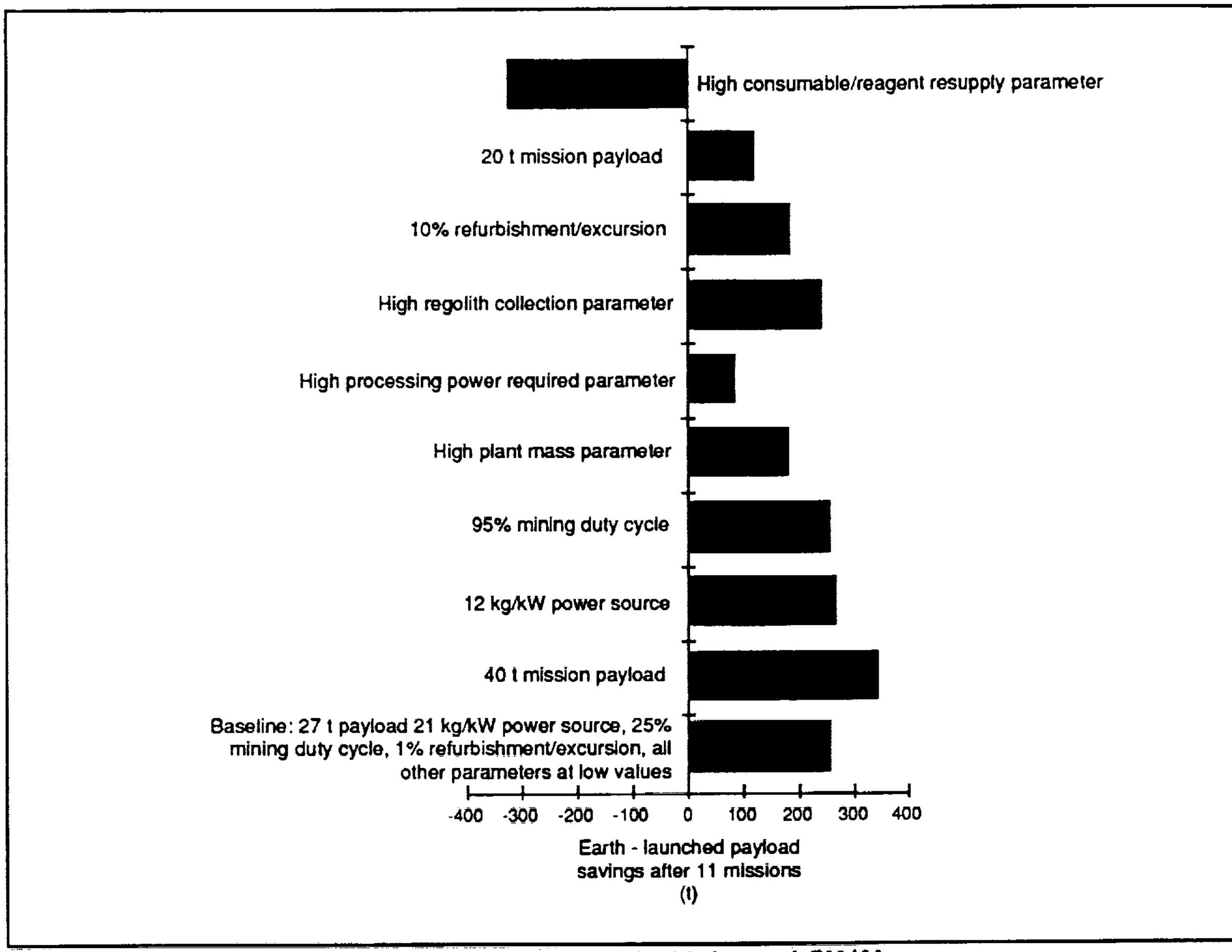


Figure 6-4: Earth-Launched Mass Savings Potential with Lunar LOX/Al

resupply value had a significantly higher cumulative Earth-launched payload than the baseline. This is explained by the low steady-state savings offered by this case; it is not due to an excessively large up-front investment. The low savings seen for the case which uses the high estimate for processing power required is due to the up-front investment and has comparable steady-state benefits (see Figure 6-3) to the baseline. This suggests that steady-state operation requirements, which are strongly driven by the plant's support requirements, has a greater effect on potential benefits attainable than the up-front investment required. However, if the comparison was made using fewer than 11 missions, the up-front investment would have much more influence over the Earth-launched mass savings.

For application to the Mars transfer cases, "low" values (Section 3) for plant design and resupply parameter values were selected to represent the lunar propellant production system requirements. If a substantial benefit cannot be shown using this optimistic representation of lunar propellant production requirements, it is very likely that their use for support of a Mars mission would not provide a benefit within a reasonable time frame.

Because this analysis covers multiple missions to Mars, spanning several launch opportunities, we selected averaged Mars mission energy requirements from several opposition class opportunities in the interval 2016-2030. The ΔV values used are shown in Table 6-1. These values assume all-propulsive trajectory design. Using actual opportunity-dependent impulses would impact propellant production rates; extreme variations could affect plant sizing requirements as well. However, this average value characterization is applied to all cases, with and without ISPP, for this analysis

TABLE 6-1
MARS ROUND TRIP IMPULSE REQUIREMENTS

Trans-Mars Injection Point	Burn	ΔV (km/s)
Low Earth Orbit	TMI	3.982
	MOI	2.590
	TEI	2.521
	EOI	4.081
Low Lunar Orbit	TMI	2.005
(excludes LEO-to-LLO:	MOI	2.590
TLI = 3.300 km/s	TEI	2.521
LOI = 1.110 km/s)	EOI	4.081

6.3 PROPELLANT UTILIZATION: MISSION DESIGN ALTERNATIVES

ISPP infrastructure requirements depend on the propellant(s) manufactured, the manufacturing location (Moon, Mars), and the application. For this study, three applications have been investigated. The first uses only lunar-derived propellant for both the outbound and return Mars trips. The second uses propellant from Earth for the outbound trip, and Mars-produced propellant for the return trip. The third application uses lunar-produced propellant for the outbound trip and Mars-produced propellant for the return trip. Table 6-2 summarizes the infrastructure elements included in each of these utilization strategies. The transfer and excursion vehicles serve nearly the same role as they do in the baseline case; the table entries describe how each vehicle supports the ISPP application. Also included are initial delivery, resupply, and change-out of the chemical plant, and an expendable stage for LEO to LLO transportation when required. The two strategies that use lunar-derived propellants use the "3-leg" mission profile described in Section 5.

TABLE 6-2
SUMMARY OF TRANSPORTATION AND INFRASTRUCTURE ELEMENTS

ELEMENT	UTILIZATION STRATEGY *Lunar Propellant Only*	 *Mars Propellant Only*	 *Lunar and Mars Propellant*
Mars mission payload	Delivered to LEO from Earth (25 t)	Delivered to LEO from Earth (25 t)	Delivered to LEO from Earth (25 t)
MEV	Initially brought to Mars and reused for 5 missions; fueled with lunar propellant in LMO with enough propellant to carry the Mars mission payload down and return to LMO for next mission	Initially brought to Mars and reused for 5 missions; fueled on the Mars surface with enough propellant to deliver MTV return propellant to LMO and to carry the Mars mission payload and Mars plant refurbishment/resupply down	Initially brought to Mars and reused for 5 missions; fueled on the Mars surface with enough propellant to deliver MTV return propellant to LMO and to carry the Mars mission payload and Mars plant refurbishment/resupply down
MTV	Carried to LLO from LEO on expendable stage; fueled in LLO for trip to Mars and return to LEO with additional propellant to refuel the MEV in LMO	Carries the Mars mission payload and Mars plant refurbishment/resupply to LMO using Earth delivered LOX/H2; refuels in LMO for return trip	Carries the Mars mission payload and Mars plant refurbishment/resupply to LMO from LLO using lunar produced propellant; refuels in LMO with Mars produced propellant for the return trip; boosted to LLO from LEO on the expendable stage
LEV	Initially brought to the Moon and reused for 5 missions; refueled on lunar surface to carry MTV and MEV propellant up and bring lunar plant resupply down		Initially brought to the Moon and reused for 5 missions; refueled on lunar surface to carry MTV outbound propellant up and bring lunar plant resupply down
Expendable LOX/H2 stage	Brought to LEO from Earth to boost MTV + Mars mission payload + lunar plant refurbishment/resupply to LLO; resized for the initial plant set-up and for missions where LEV, MTV, and MEV are replaced		Brought to LEO from Earth to boost MTV + Mars mission payload + lunar & Mars plant refurbishment/resupply to LLO; resized for the initial plant set-up and for missions where LEV, MTV, and MEV are replaced
Lunar propellant plant	Produces all propellant used in the LEV, MTV, and MEV		Produces all propellant used in the LEV and for the MTV outbound trip
Lunar propellant plant refurbishment/ resupply	Brought to LLO on the expendable stage and carried to the surface on the LEV		Brought to LLO on the expendable stage and carried to the surface on the LEV
Mars propellant plant		Initially brought to LMO with an expendable stage; produces propellant for MEV round trip and MTV return trip	Initially brought to LMO with an expendable stage; produces propellant for MEV round trip and MTV return trip
Mars propellant plant refurbishment/ resupply		Brought from LEO on MTV with the Mars mission payload	Brought from LEO on MTV with the Mars mission payload

Lunar Propellant for Outbound and Return. This strategy exchanges Earth propellant for lunar derived propellant for the Mars round trip. It uses an expendable LOX/H_2 stage to boost the Mars vehicles and payloads from LEO to LLO, where lunar-derived propellant is loaded. The MTV departs for Mars from LLO. The MTV returns from Mars to LEO for reuse; it picks up a new mission payload and refurbishment/resupply items for the lunar propellant plant. Figure 6-5 shows a profile of the steady-state operation mode for this approach, and Table 6-3 summarizes the infrastructure assessment. Three cases were assessed for this strategy, each using a different propellant combination: LOX/Al, LOX/Si, and LOX with Earth-source H_2. Of the three, only the LOX with Earth-sourced H_2 case showed a savings in Earth-delivered mass over the course of 11 missions. An 11 mission time line was chosen to include requirements through two life cycles of the transfer and excursion vehicles.

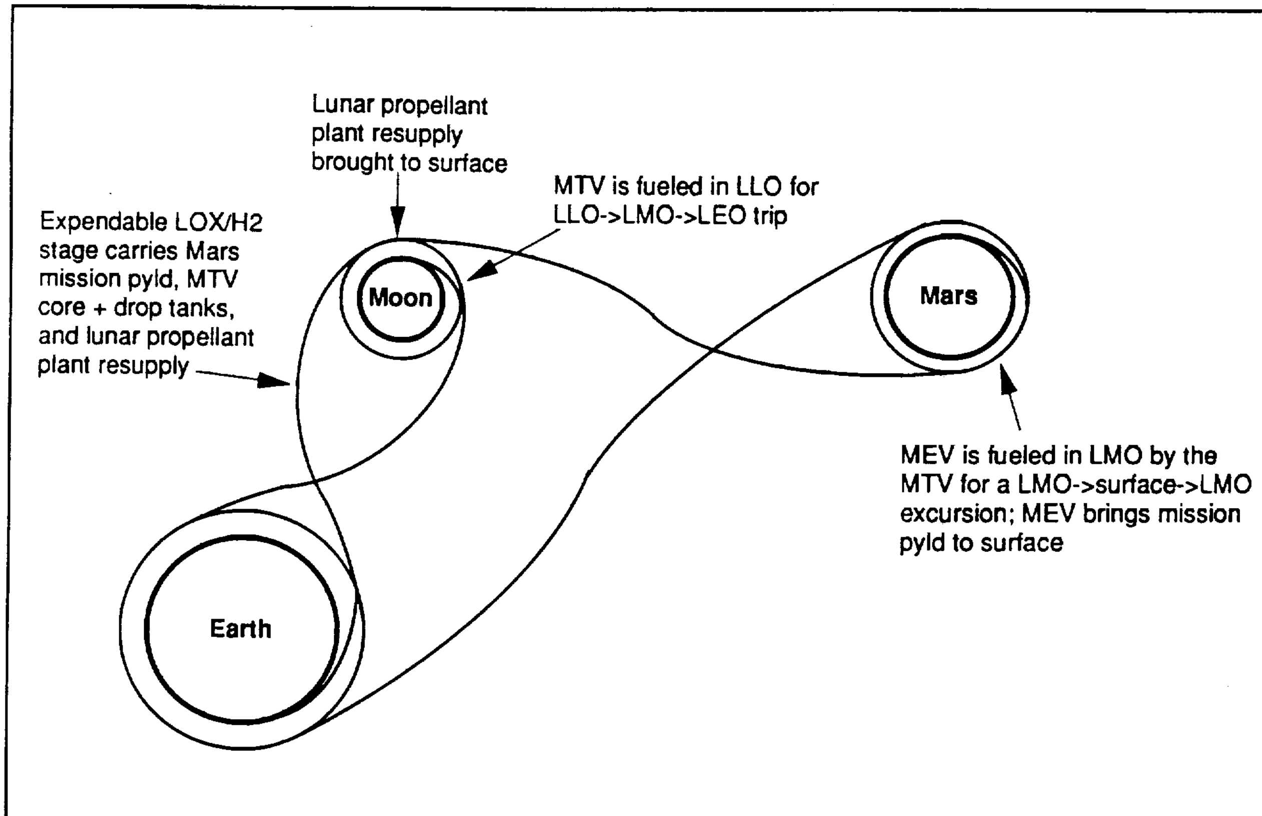


FIGURE 6-5: Mission Profile for Lunar Propellant Use

The lunar propellant only results using lunar-sourced LOX/Al are shown in Figure 6-6. Mission #0 is so labelled because the Earth-delivered mass requirements do not include delivery of the Mars mission payload and only account for requirements to establish the propellant plant systems and infrastructure. As such, "Mission #0" is only a placeholder to count initial delivery mass requirements in this analysis; actual delivery of these elements could take place over one or more flights. Missions #1-11 each deliver the 25 t Mars mission payload. The peaks observed at missions #6 and #11 represent Earth-delivered mass requirements

TABLE 6-3
INFRASTRUCTURE ASSESSMENT FOR LUNAR PROPELLANT MANUFACTURE

	Lunar Propellant Only Scenario Assumptions
Set-Up of Propellant Plant & Infrastructure	• Launched from Earth to LEO: 2 LEVs, 1 expendable stage, lunar propellant plant • Expendable stage uses Earth-sourced LOX/H2 • Expendable stage carries plant + LEVs to LLO from LEO • The LEVs always use the propellant being produced at the Moon, initially supplied from Earth for plant set-up mission • Each LEV, loaded with enough propellant to carry down 1/2 the plant mass • One LEV is not used in steady-state operation and remains on surface as a spare • Specialized hardware for plant set-up is accounted for by adding 5% of the plant mass to the payload
Steady-State Operation	• Launched from Earth: Expendable stage with propellant, MTV drop tanks, MEV aerobrake, resupply for the lunar plant, Mars mission payload (with crew) • Expendable stage carries lunar plant resupply, MTV, MEV aerobrake, and Mars mission payload to LLO • 1 LEV ascends from lunar surface using lunar propellant and carries MTV and MEV round trip propellant • Propellant is transferred to MTV and plant resupply materials transferred to the LEV • If using in situ LOX with Earth H2, H2 for the next mission round trip (ascent-descent) is loaded on the LEV prior to LEV descent • MTV departs LLO to LMO • MTV meets MEV in LMO and transfers Mars mission payload and propellant for a MEV round trip (descent-ascent) • MEV descends to surface with Mars mission payload • MEV ascends to LMO to return crew to MTV
Transfer/Excursion Vehicle Changeout	• Launched from Earth: Expendable stage with propellant, LEV with propellant for descent, MTV, MEV with aerobrake, resupply for the lunar plant, Mars mission payload (with crew) • Mission proceeds same as steady-state except the new excursion vehicles are used to bring payloads to lunar and Mars surface • Vehicles are changed out every 5 missions, set-up mission not counted, vehicles changed out on missions #6 and #11
Propellant Plant	• Propellant plant produces propellant to support the LEV, MTV, and MEV • Propellant storage sized to accommodate 2 times the amount of propellant needed to support 1 mission • Plant requirements include all systems necessary to collect raw lunar material, process it to extract propellant candidate, and store produced propellants

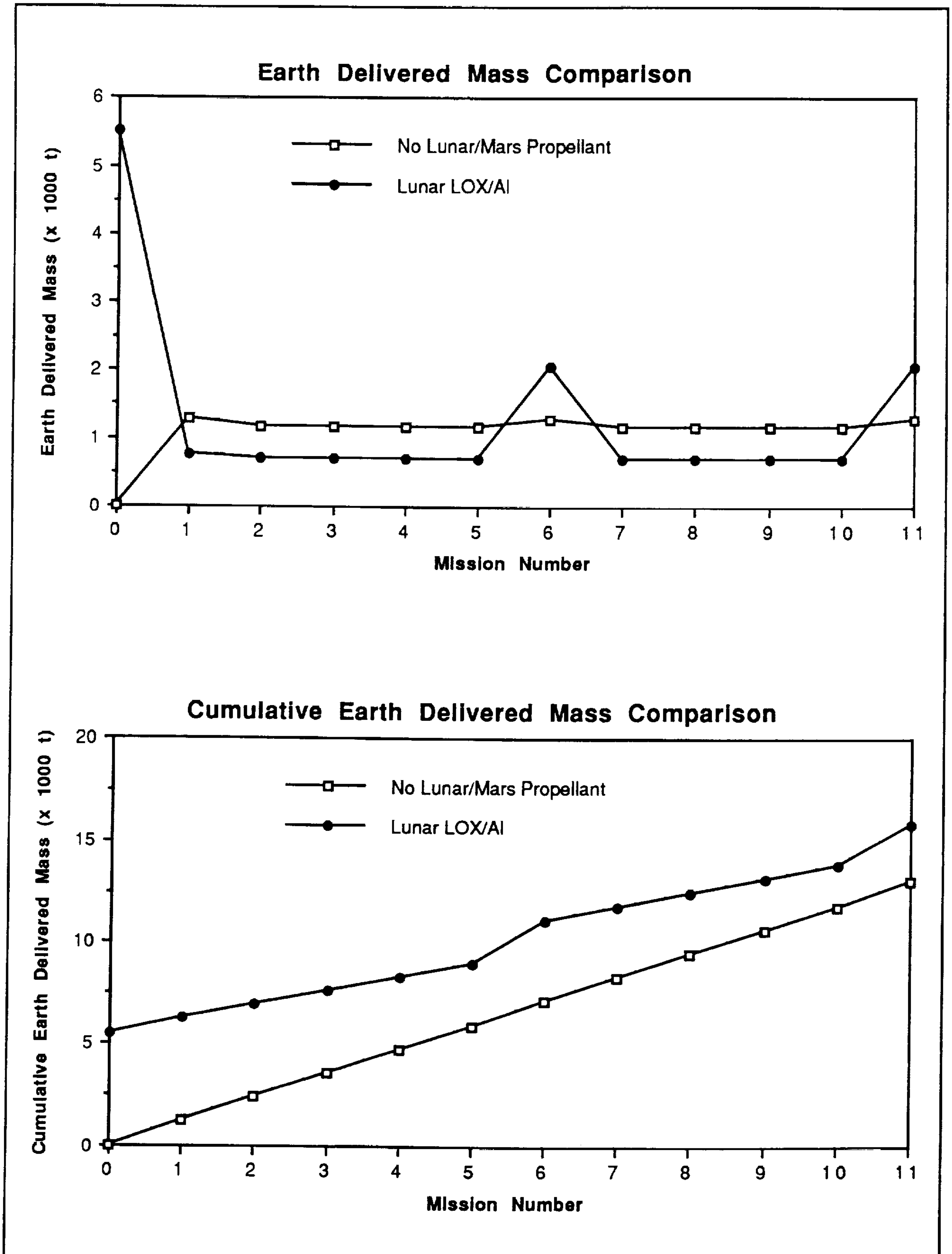


FIGURE 6-6: Lunar LOX/Al

for the missions that change out space transportation vehicles at the end of their useful life of five flights. The pattern established from mission #7 through mission #11 would continue, assuming no change in technology or payload mass delivered to the surface.

The Earth-delivered mass at mission #0 includes the lunar propellant plant and specialized plant set-up hardware, two lunar excursion vehicles loaded with enough LOX/Al from Earth (LEV propellant) to carry the plant down to the lunar surface from low-lunar orbit, and an expendable LOX/H_2 stage to transport these masses to LLO from LEO. The first Mars mission, mission #1, has a slightly higher Earth-delivered mass than steady-state requirements because it carries the MEV to Mars. In the steady-state mode, the Earth-delivered mass consists of the lunar plant support, Mars mission payload, MTV drop tanks, an aerodeceleration module for the MEV, and the expendable stage to boost these payloads to LLO from LEO.

The Earth-delivered mass requirements for the vehicle change-out missions, #6 and #11, are significantly higher for the cases using lunar propellant than for the baseline performance without ISPP. The reason for this is that more vehicles are being replaced in the ISPP case. In the baseline case which does not use ISPP, one MTV and one MEV are used; the ISPP cases add two LEVs to transport propellant from the Moon. Also, the LEV mass is large because it must be sized with tanks to carry enough propellant for the MTV and MEV round trips. In summary, this case did not show an advantage for ISPP over the course of 11 missions.

Figure 6-7 shows the results using lunar LOX/Si instead of LOX/Al. The trade here is one of propulsion system performance versus propellant production requirements. Although the performance of LOX/Si propulsion is not as good as for LOX/Al propulsion, the requirements for producing LOX/Si from lunar materials are lower. The Earth-delivered mass for this case is slightly lower than for the LOX/Al case, but still no Earth-delivered mass savings is realized after 11 missions.

Figure 6-8 shows the results using lunar LOX with Earth-sourced hydrogen; note the change of scale on the upper graph. This case differs from the LOX/Al and LOX/Si cases because the Earth-delivered mass requirements now account for delivery of hydrogen. Propellant utilization assumptions are also somewhat different for the LEV. The LEV is assumed to bring enough hydrogen for a LEV round trip in addition to the plant support down to the surface. The LEV uses this hydrogen for its round trip on the next mission. This case takes advantage of lower propellant plant requirements because only the oxygen is being produced. Steady-state Earth-delivered mass requirements are lower for this case compared to the LOX/Al and LOX/Si cases. Also, some Earth-delivered mass savings are realized over the course of 11 missions. In this case, Mission #3 shows a break-even for ISPP; the savings would continue to grow as the number of flights increases.

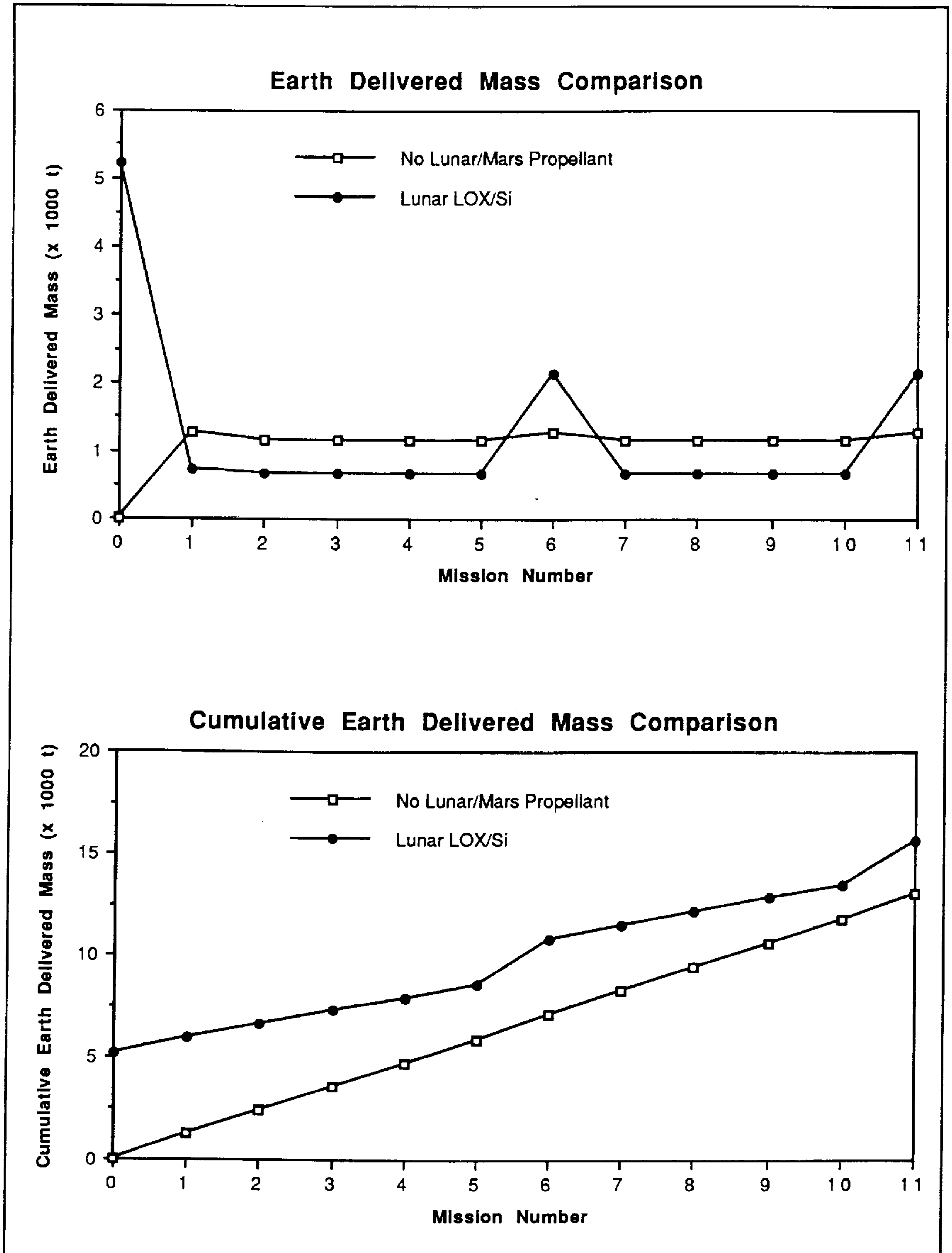
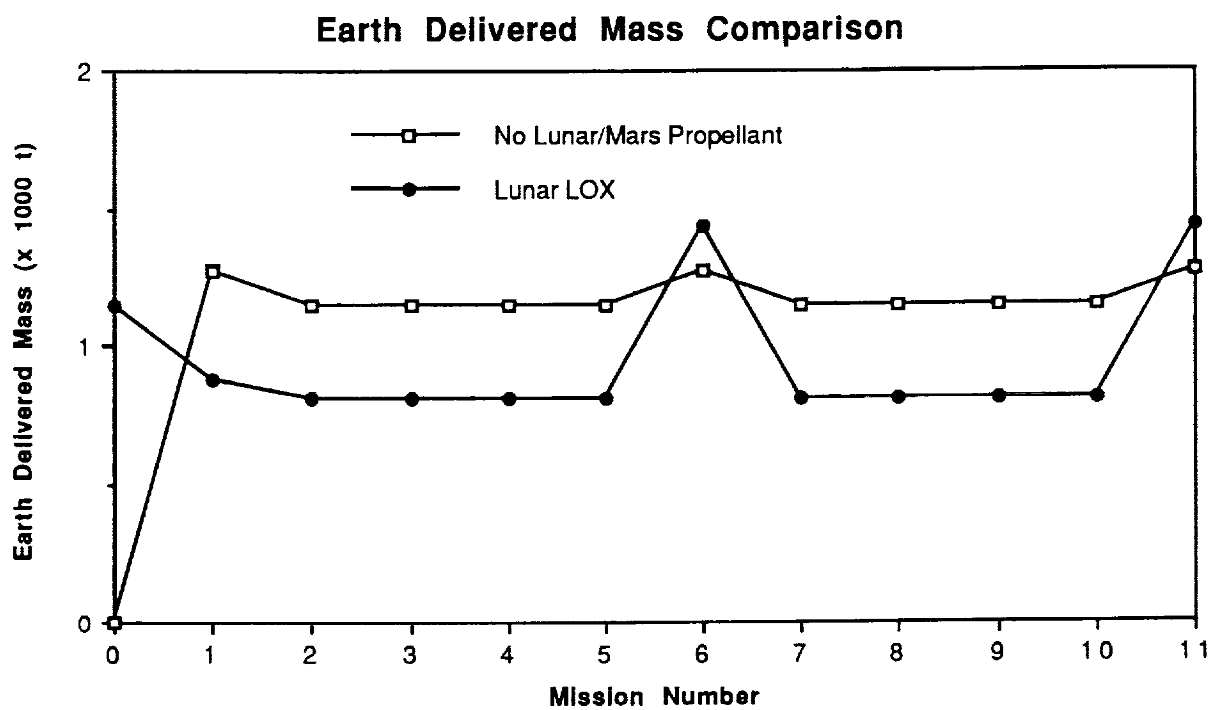


FIGURE 6-7: Lunar LOX/Si



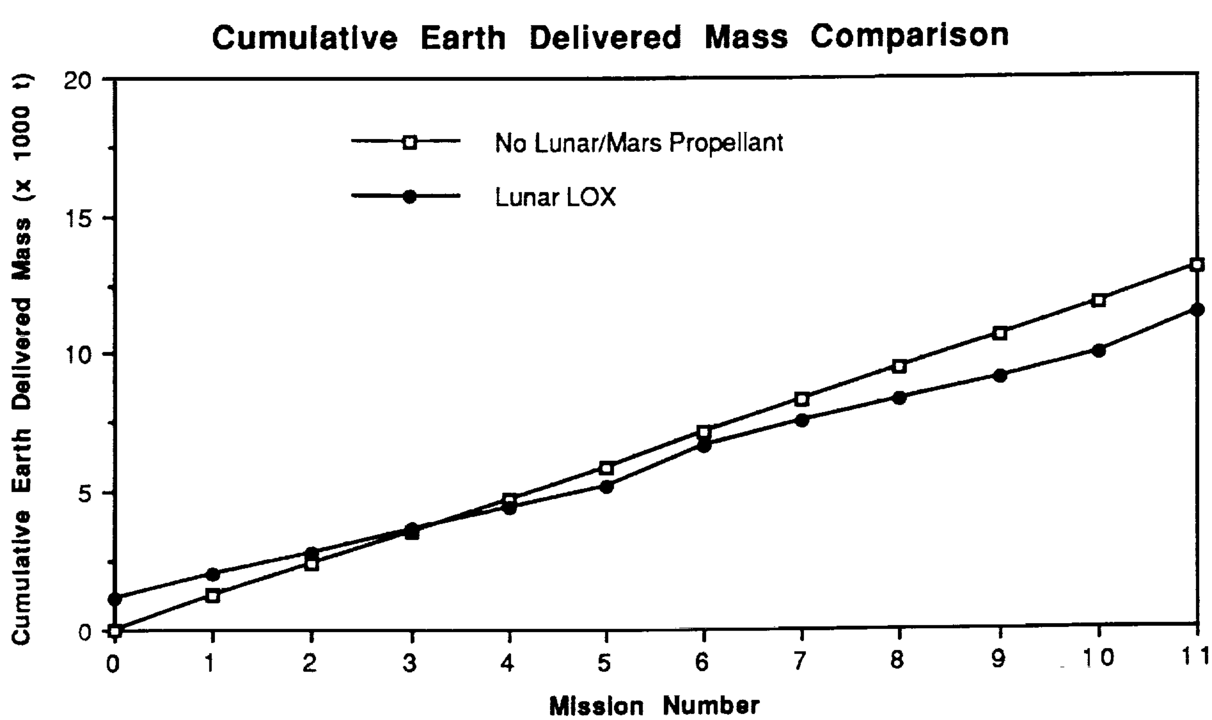


FIGURE 6-8: Lunar LOX with Earth LH

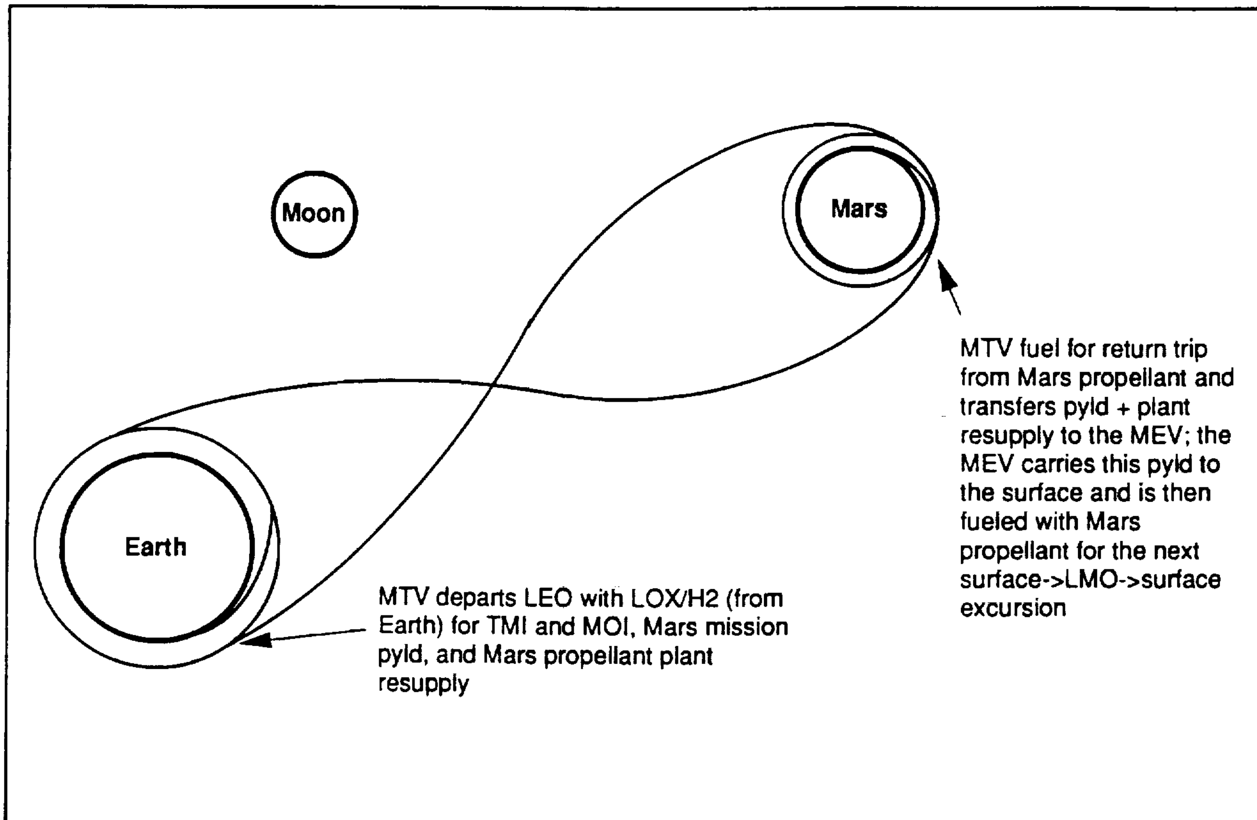


FIGURE 6-9: Mission Profile for Mars Propellant Use

Mars Propellant for Return. The Mars propellant only scenario is shown in Figure 6-9. The MTV leaves LEO with Earth-sourced LOX/H_2 and refuels in LMO with Mars-derived propellant. The MEV is fueled entirely on Mars-derived propellant. A case where the MTV is fueled entirely on Mars-derived propellant was also examined. Because this case could not take advantage of staging (i.e., all the tanks need to be carried throughout the round trip), the Earth-delivered mass requirements were significantly larger than the other Mars propellant only cases. This approach was not considered further.

Three cases were investigated for this scenario, each using a different Mars-sourced propellant for the return to Earth. The propellant combinations included LOX/CH_4, LOX/CO, and Mars LOX with Earth-derived H_2. The availability of hydrogen or water on Mars was not assumed for this study. Table 6-4 defines the infrastructure.

Figure 6-10 shows the results for producing LOX/CH_4 at Mars. Mission #0 requirements are based on delivery of a LOX/CH_4 propellant plant using the MTV and MEV. The MEV is supplied with the propellant it needs to bring the plant down to the Mars surface. At mission #1, the propellant plant is operational and is producing propellant for the MEV and the MTV return trip. A new MTV and MEV are supplied for missions #5 and #10 when using Mars-produced propellant. This is one mission earlier than the previous cases that do not use Mars-produced propellant, because the vehicles get their first use at mission #0 to deliver the

TABLE 6-4
INFRASTRUCTURE ASSESSMENT FOR MARS PROPELLANT MANUFACTURE

	Mars Propellant Only Scenario Assumptions
Set-Up of Propellant Plant & Infrastructure	• Launched from Earth to LEO: MTV, MEV with aerobrake, Mars propellant plant • MTV uses Earth LOX/H2 for round trip • MEV loaded with Earth-sourced propellant to descend to surface with propellant plant • MTV carries MEV and Mars propellant plant to LMO from LEO • MEV descends to surface with propellant plant • Specialized hardware for set-up is accounted for by adding 5% of the plant mass to the payload
Steady-State Operation	• Launched from Earth: MTV drop tanks, MEV aerobrake, resupply for the Mars plant, Mars mission payload (with crew) • MTV, using Earth LOX/H2 for the outbound leg, transfers to LMO from LEO • MEV meets MTV in LMO • MTV transfers Mars plant resupply, MEV aerobrake, and Mars mission payload to MEV • If using in situ LOX with Earth H2, round trip (descent-ascent) MEV H2 is transferred from MTV to MEV in LMO • MEV descends to surface with plant resupply and Mars mission payload • MEV refueled with Mars propellant for round trip (ascent-descent) • MEV ascends to LMO and transfers crew and Mars propellant for the MTV return leg to the MTV • If using in situ LOX with Earth H2, the MEV ascends to LMO arriving with LOX for the next mission's descent but no H2
Transfer/Excursion Vehicle Changeout	• Launched from Earth: MTV, MEV with aerobrake, resupply for the Mars plant, Mars mission payload (with crew) • Mission proceeds same as steady-state except a new excursion vehicle is used to bring payloads to the Mars surface (descent propellant from Earth) • Vehicle are changed out every 5 missions • Because the MTV and MEV are used in the set-up mission, they are replaced one mission earlier than in the baseline, or no-Mars propellant, scenario
Propellant Plant	• Propellant plant produces propellant to support the MEV and MTV return trip • Propellant storage sized to accommodate 2 times the amount of propellant needed to support 1 mission • Plant requirements include all systems necessary to collect Martian atmosphere, process it to extract propellant candidate, and store produced propellants

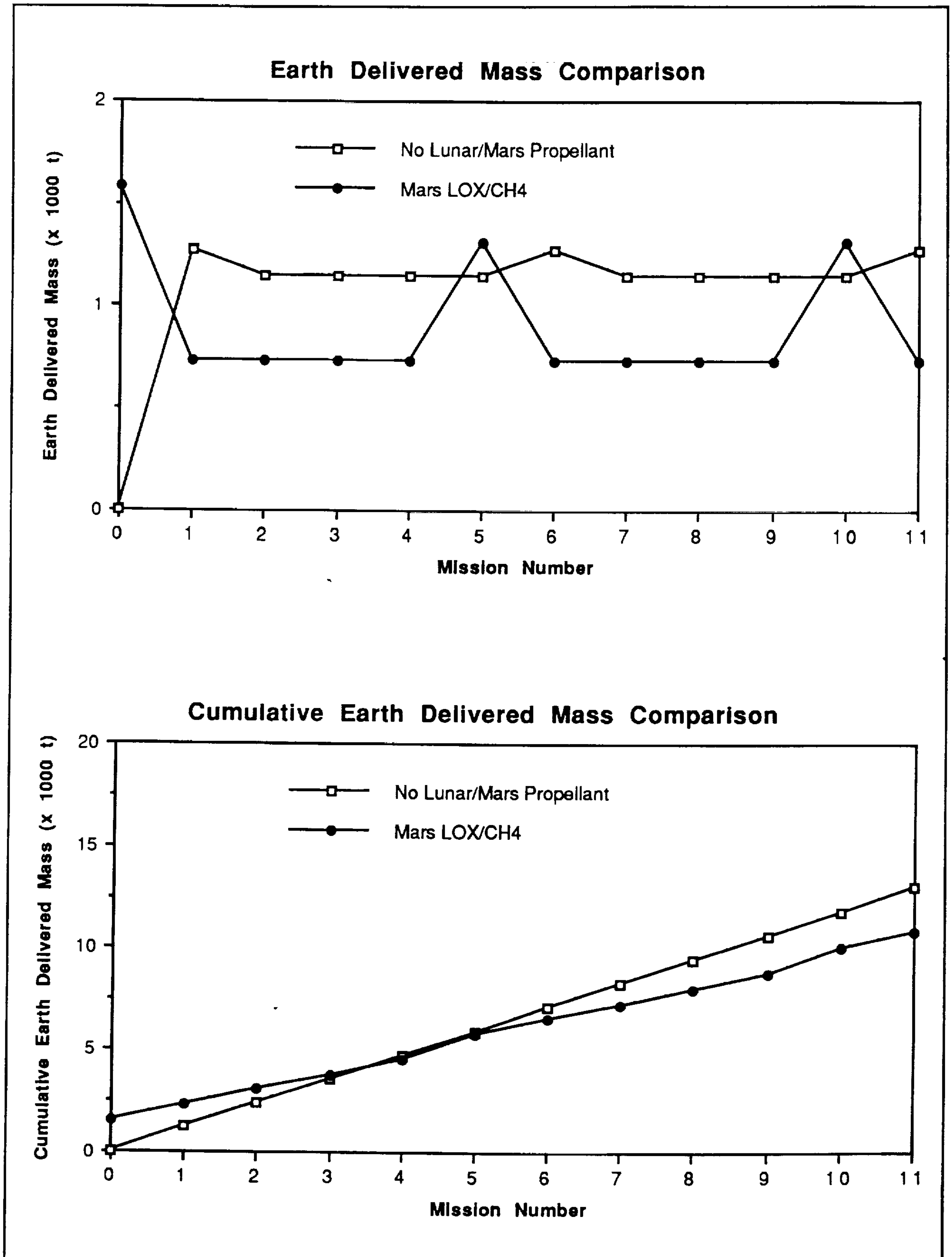


FIGURE 6-10: Mars LOX/CH_4

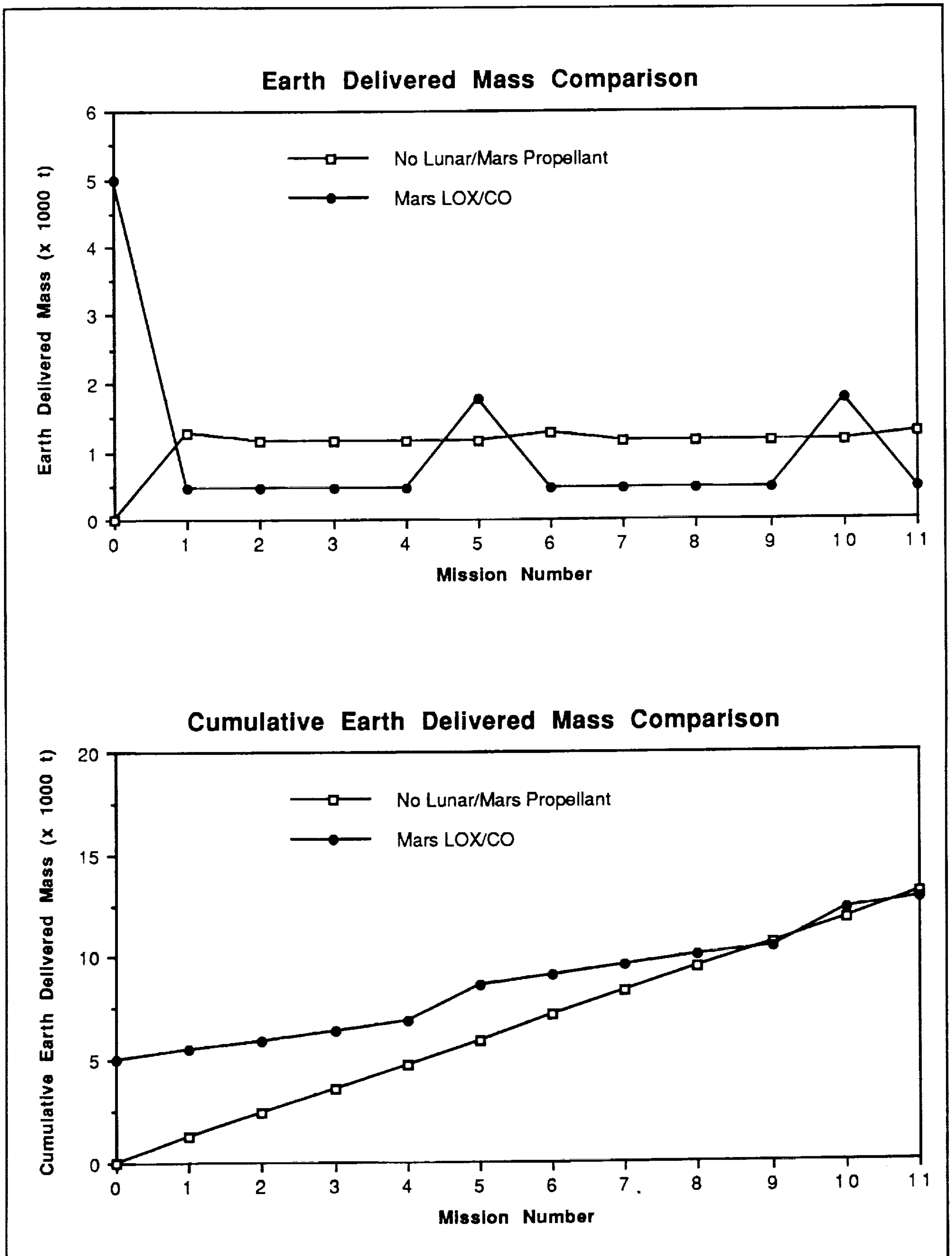


FIGURE 6-11: Mars LOX/CO

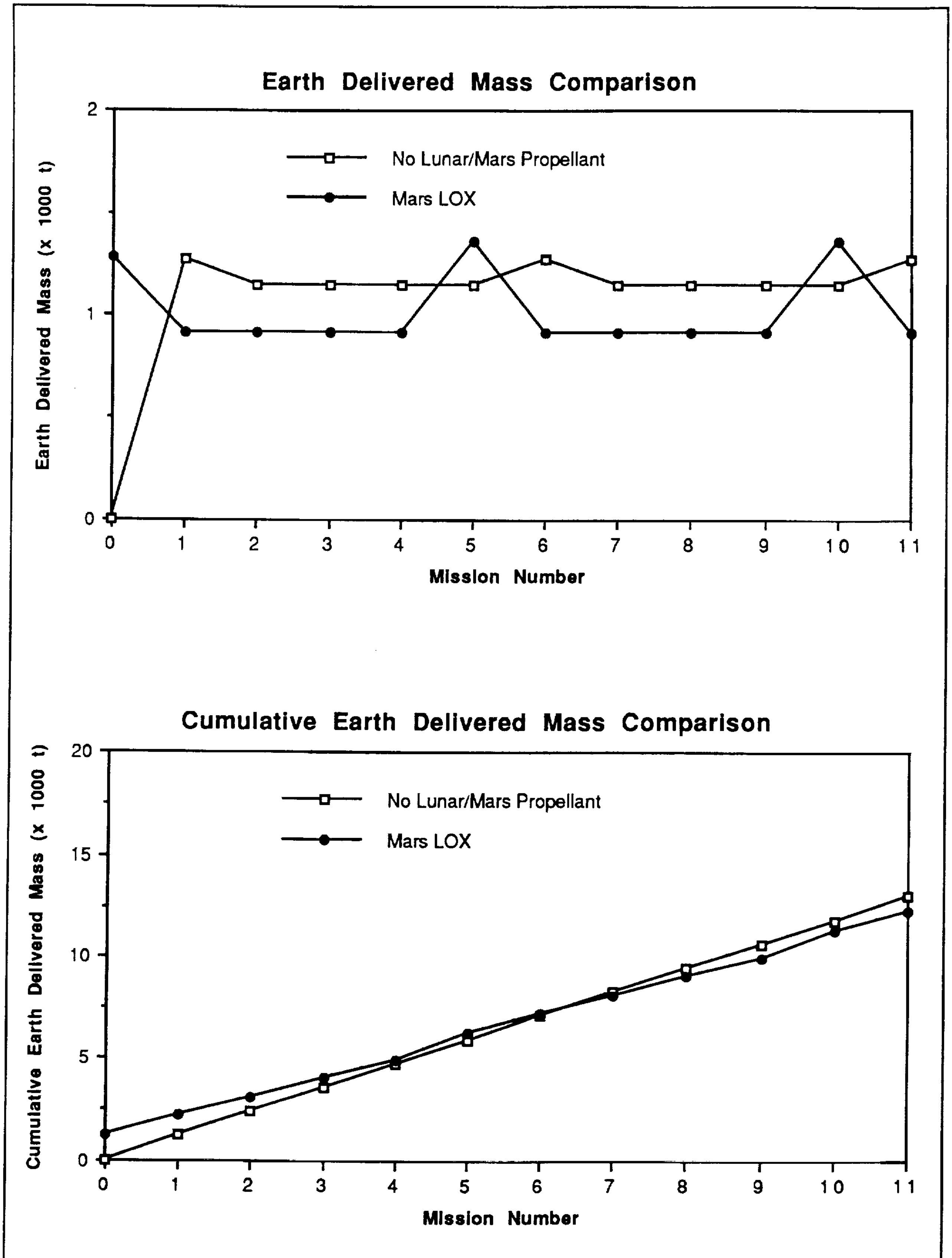


FIGURE 6-12: Mars LOX with Earth LH

propellant plant. Over 80% of plant support in this case is due to resupply of hydrogen for methane production.

Figure 6-11 shows the results for the LOX/CO case. The high Earth-delivered mass requirement at mission #0 reflects delivery of the refrigeration equipment for separating CO from a CO-CO_2 mixture, and the high propellant production rate needed to support lower specific impulse LOX/CO propulsion systems used for Mars missions. Even though the steady-state performance of this system shows more benefit than in the LOX/CH_4 case, the high Earth-delivered mass requirement for plant set-up pushes the number of missions to mass payback beyond the range of an 11 mission time line.

The simplest processing scheme for producing Mars propellant would be the case where only Mars LOX is produced and hydrogen is supplied from Earth. This case, shown in Figure 6-12, has a relatively low Earth-delivered mass requirement for plant set-up, but does not provide a significant benefit for steady-state operation: ongoing hydrogen supply and plant refurbishment needs offset the lower setup cost. Only a small reduction in cumulative Earth-delivered mass is realized after 11 uses in Mars round trip missions -- probably not enough to justify the investment.

Lunar Outbound and Mars Return Propellant. For this scenario, lunar produced propellant is used to fuel the MTV for a LLO to LMO trip and Mars produced propellant is used to fuel the MTV for a return trip to LEO. An expendable stage is used to move the empty MTV, with tankage, lunar and Mars plant support, and the Mars mission payload from LEO to LLO where the cycle repeats. This scenario is shown schematically in Figure 6-13, and the assessment details are shown in Table 6-5.

Several cases were assessed for this strategy, but they are a subset of the possible alternatives. For the Moon, LOX/Si was selected over LOX/Al due to its better performance in the lunar propellant only strategy. For Mars, LOX/CH_4 was selected over LOX/CO due to its better performance in the Mars propellant only strategy. The option of producing only LOX at the Moon and at Mars was also included. In addition to these cases, a case was investigated that used LOX/CH_4 produced at both the Moon and Mars. LOX/CH_4 produced at the Moon was not investigated for the lunar propellant only strategy, but is included here because it is one of two candidate propellant combinations that could be produced at the Moon and Mars (the other being LOX/CO).

Figure 6-14 shows the requirements for a case that uses lunar LOX/Si and Mars LOX/CH_4. In the steady-state mode, this case shows significant benefit compared to the baseline, although the high Earth-delivered mass requirement for set-up of the two propellant plants shifts the number of missions to mass payback to about five missions. For the set-up requirements at mission #0, two LEVs bring the lunar plant to the

TABLE 6-5
INFRASTRUCTURE ASSESSMENT FOR LUNAR AND MARS PROPELLANT MANUFACTURE

	Lunar & Mars Propellant Scenario Assumptions
Set-Up of Propellant Plant & Infrastructure	• Launched from Earth to LEO: 2 LEVs, 1 expendable stage, MTV, MEV with aerobrake, lunar and Mars propellant plants • Expendable stage uses Earth-sourced LOX/H2 • Expendable stage carries both plants + LEVs + MEV + MTV to LLO from LEO • The LEVs use the propellant being produced at the Moon and the MEV uses the propellant being produced at Mars • Each LEV is loaded with enough propellant to carry down 1/2 the lunar plant mass • One LEV is not used in steady-state operation and remains on surface as a spare • The MEV is loaded with enough propellant to carry down the Mars plant • The MTV is fueled from Earth with LOX/H2 for the round trip (LLO->LMO->LEO) • Specialized hardware for set-up is accounted for by adding 5% each plant's mass to the payload
Steady-State Operation	• Launched from Earth: Expendable stage with propellant, MTV drop tanks, MEV aerobrake, resupply for both propellant plants, Mars mission payload (with crew) • Expendable stage transfers to LLO from LEO • LEV ascends to LLO with MTV outbound propellant and transfers this propellant to MTV • MTV transfers lunar plant resupply to LEV • LEV descends to lunar surface with plant resupply • MTV departs LLO and meets MEV in LMO • MTV transfers Mars plant resupply and Mars mission payload (with crew) to MEV • MEV descends to surface and is then refueled for a round trip (ascent-descent) • MEV ascends to LMO with MTV return propellant (and crew) • If using in situ LOX with Earth H2, the LEV will obtain its round trip H2 from the MTV in LLO and carry it to the surface to be used on the next mission; the MEV obtains its round trip H2 from the MTV in LMO and uses part of this H2 to descend to the surface arriving with enough H2 for ascent; on the surface, the MEV then refuels with LOX for a round trip (ascent-descent) on the surface
Transfer/Excursion Vehicle Changeout	• Launched from Earth: Expendable stage with propellant, MTV, LEV, MEV with aerobrake, down propellant for each new excursion vehicle, resupply for both propellant plants, Mars mission payload (with crew) • Mission proceeds same as steady-state except the new excursion vehicles are used to bring payloads to the lunar and Mars surface • Vehicles are changed out every 5 missions • Because the MTV, LEV, and MEV are used in the set-up mission, they are replaced one mission earlier than in the baseline, or no-lunar/Mars propellant, scenario
Propellant Plant	• Lunar propellant plant produces propellant to support the LEV and the MTV outbound leg • Mars propellant plant produces propellant to support the MEV and the MTV return leg • Propellant storage sized to accommodated 2 times the amount of propellant needed to support 1 mission • Plant requirements include all systems necessary to collect feedstock, process feedstock to extract propellant candidate, and store produced propellants

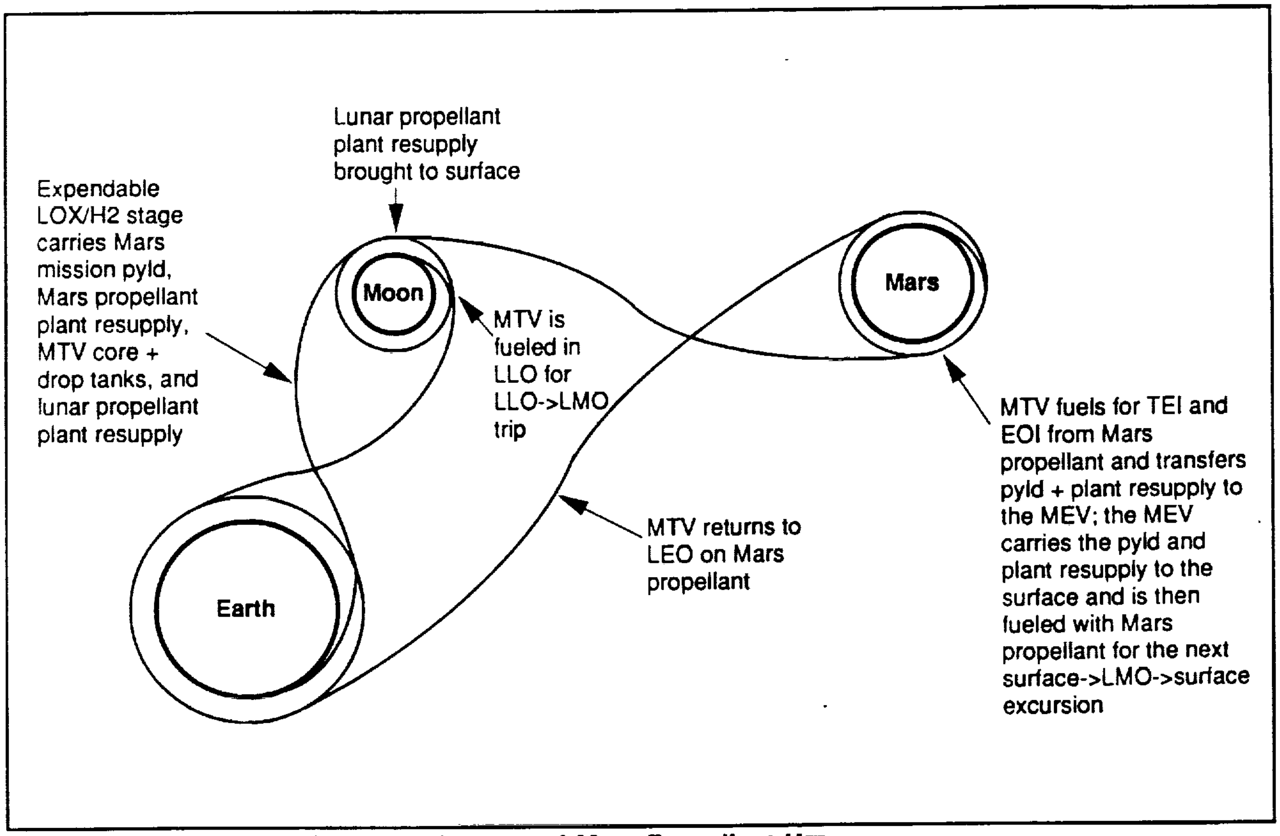


FIGURE 6-13: Mission Profile for Lunar and Mars Propellant Use

surface and the MEV brings down the Mars plant. The MTV is also used for this plant set-up mission. Because these vehicles are being used to deliver the propellant plants at mission #0, they are replaced one mission earlier than in the case which does not use lunar/Mars propellant. Missions #5 and #10 include one new LEV, an MEV, and an MTV, as well as planned support for both plants and the Mars mission payload.

A case using lunar LOX with Earth-supplied hydrogen for the outbound trip and Mars LOX/CH_4 for the return trip is shown in Figure 6-15. Although this case has a lower Earth-delivered mass requirement for plant set-up than the previous case, the benefits realized in steady-state mode are also lower because of the continuing requirement to transport hydrogen from Earth. This results in break-even at mission #5, a slightly lower Earth-delivered mass savings after 11 missions.

If all propulsion systems use lunar or Mars produced LOX combined with Earth-supplied hydrogen, the result is a similarly long payback time, as shown in Figure 6-16. The requirement to carry all hydrogen needed for the full mission significantly reduces the benefits achievable in the steady-state mode. The plant masses at the Moon and at Mars for this case are very low; however, Earth-delivered mass requirements at mission #0 include Earth-supplied hydrogen. The net result of the assessment for this case shows a negligible mass payback at the end of the 11 mission time line.

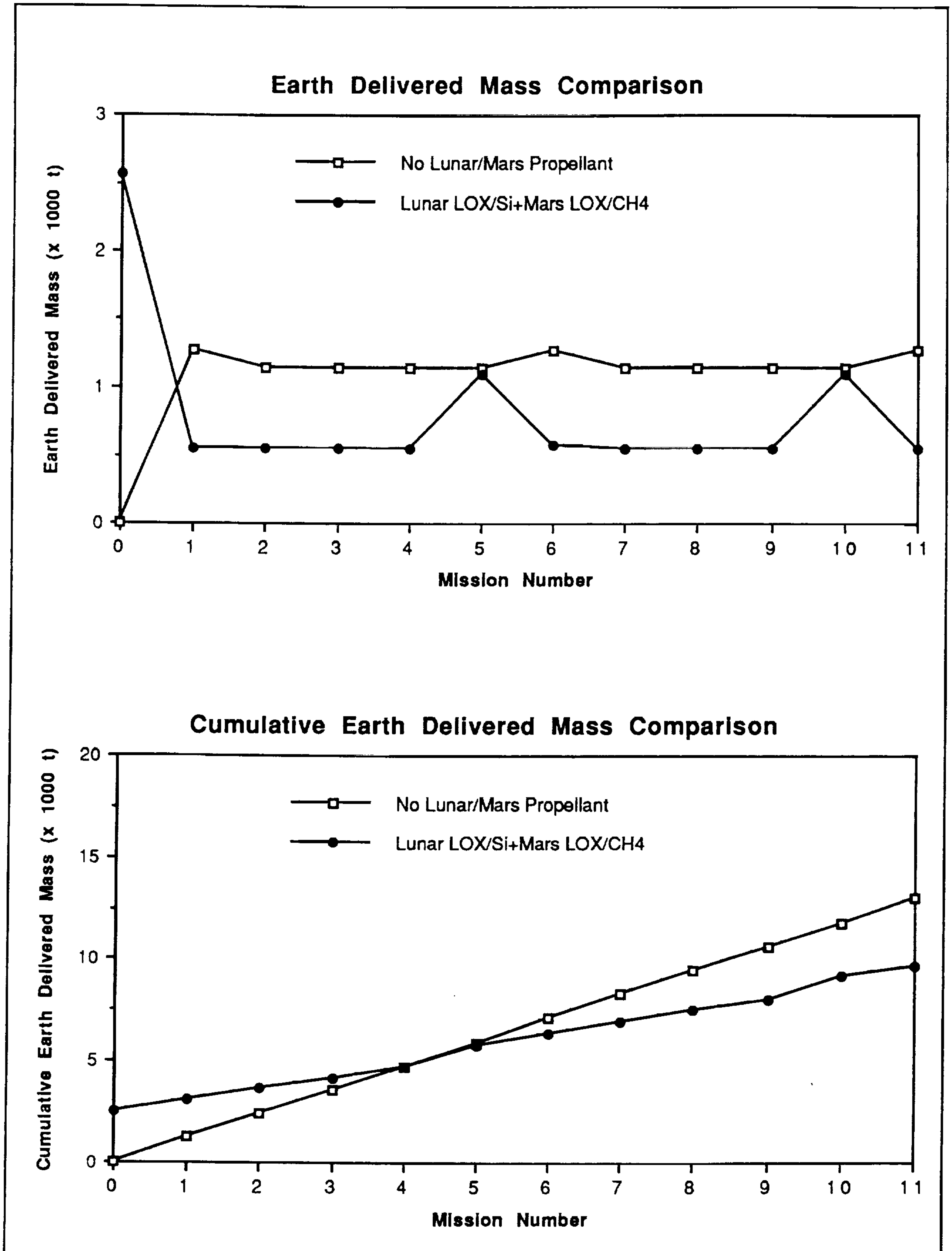


FIGURE 6-14: Lunar LOX/Si and Mars LOX/CH_4

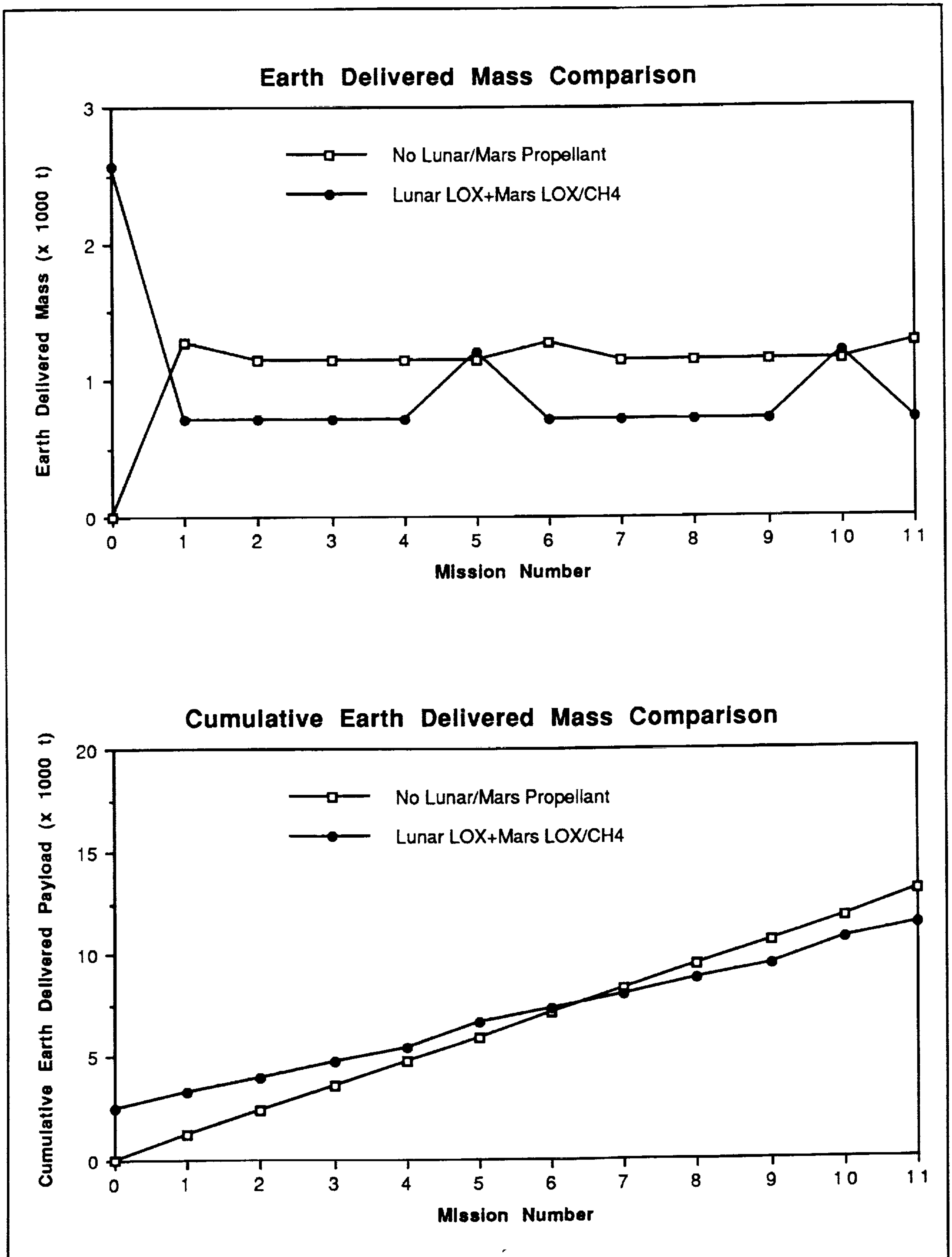


FIGURE 6-15: Lunar LOX and Mars LOX/CH_4

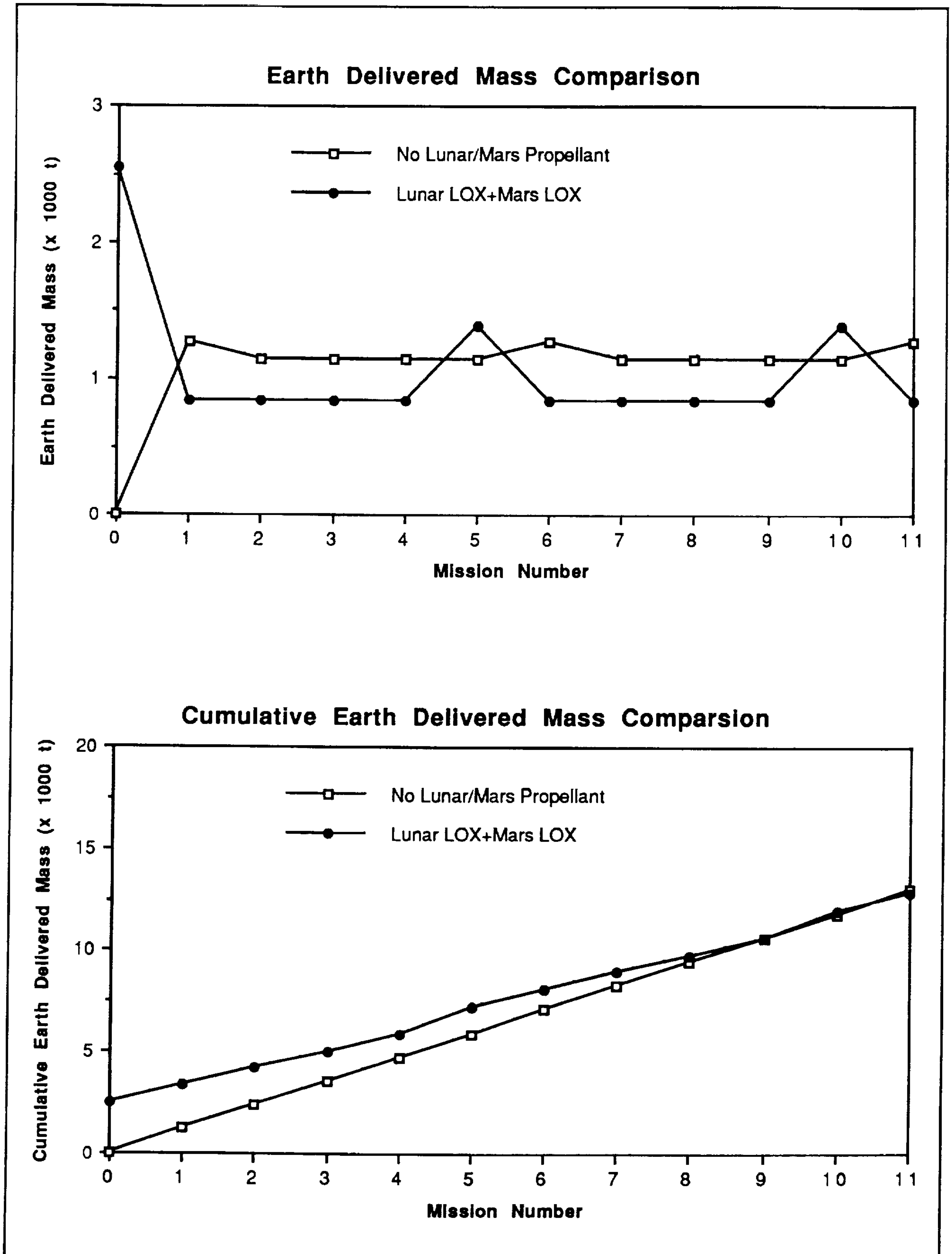


FIGURE 6-16: Lunar LOX and Mars LOX

The last case investigated for the combined lunar and Mars propellant scenario looks at Earth-delivered mass requirements using lunar and Mars produced LOX/CH_4. The results of this case are shown in Figure 6-17. This is the only case investigated with a reasonably low Earth-delivered mass requirement for set-up of propellant plants and a significantly lower Earth-delivered mass requirement in steady-state. The result is a mass payback after 3 missions and an Earth-delivered mass savings of almost 5000 t after 11 missions.

6.4 MULTI-MISSION PERFORMANCE COMPARISONS

Each case's requirements were estimated to accomplish the same mission objective: delivery of a 25 t mission payload to the surface of Mars. In all the cases using lunar/Mars produced propellants, all masses related to the plant set-up, operation, and maintenance are in addition to this mission payload. Because the use of lunar/Mars propellants is intended to reduce Earth launch needs for Mars missions, the Earth-delivered mass requirements comparison appears to be a reasonable means of comparison for this study of alternatives. Further definition of selected ISPP strategies would be needed to better represent the magnitude of actual operation requirements.

Three major factors impact performance for the cases using in situ propellants: propellant production requirements, propulsion system performance, and mission design for a propellant utilization strategy. Each of these plays a role in the multi-mission performance comparisons described in this section.

Table 6-6 provides a summary of propellant production plant characteristics for all the cases investigated. Based on our current understanding of metals production from lunar materials, it appears that the propellant plants producing LOX/Si and LOX/Al require the greatest amounts of support as compared to the other alternatives. At Mars, the production and refrigeration needs for LOX/CO require significantly higher plant mass than the other Mars propellant production alternatives. However, LOX/CO does have a relatively low support requirement. The support requirement for production of LOX/CH_4 at Mars consists of more than 80% hydrogen, which is used as a reagent in CH_4 production. If this hydrogen could be supplied from martian materials, plant support mass for this alternative could be greatly reduced.

Two questions must be addressed in assessing benefits from using lunar/Mars propellants for a Mars mission. The first is "How much initial investment is needed to establish the propellant plant operations and infrastructure?" This initial investment would include development efforts for propellant plant systems and the launch and operations costs of placing these systems on the lunar/Mars surface. Figure 6-18 shows a comparison of Earth-delivered mass requirements for plant set-up. Using lunar metals and Mars LOX/CO are the cases that stand out as requiring the most Earth-delivered mass. The cases in which only lunar or Mars LOX is produced have the lowest Earth-delivered mass requirement for plant set-up.

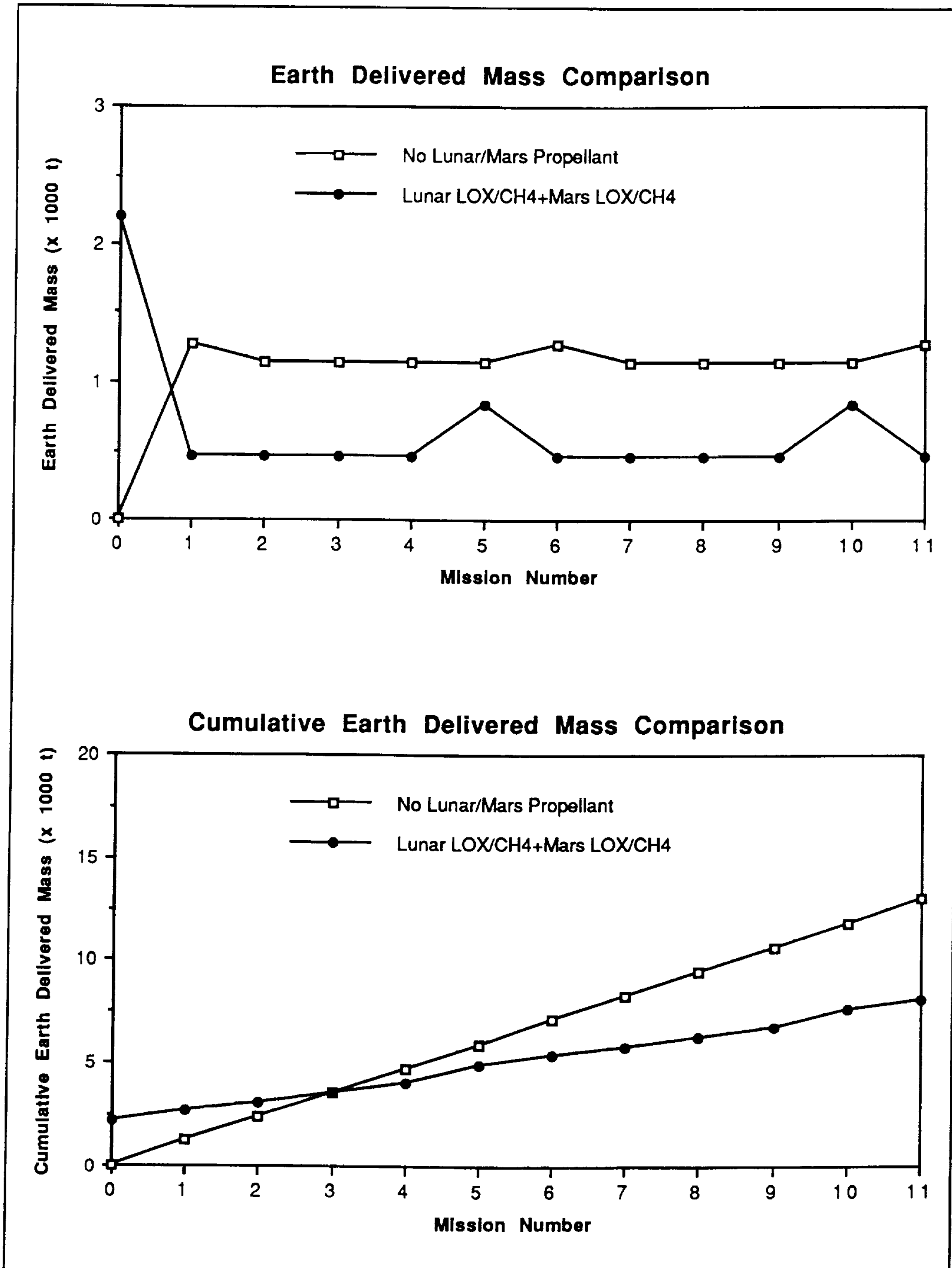


FIGURE 6-17: Lunar LOX/CH_4 and Mars LOX/CH_4

TABLE 6-6
PROPELLANT PLANT MASS SUMMARY

Scenario	Lunar Propellant Plant Production Rate (t/yr)	Lunar Propellant Plant Plant Mass * (t)	Lunar Propellant Plant Support Required ** (t/yr)	Mars Propellant Plant Production Rate (t/yr)	Mars Propellant Plant Plant Mass * (t)	Mars Propellant Plant Support Required ** (t/yr)
Lunar LOX/CH4+Mars LOX/CH4	360	70	2	685	55	38
Lunar LOX+Mars LOX	395	148	2	350	20	0.2
Lunar LOX+Mars LOX/CH4	315	118	2	685	55	38
Lunar LOX/Si+Mars LOX/CH4	855	83	18	685	55	41
Mars LOX				350	20	0.2
Mars LOX/CO				2635	465	5
Mars LOX/CH4				685	55	38
Lunar LOX	515	194	3			
Lunar LOX/Si	4695	455	32			
Lunar LOX/Al	4075	555	43			

* Plant mass includes all surface systems required from feedstock collection through propellant storage
** Support required includes hardware refurbishment and consumable reagent resupply

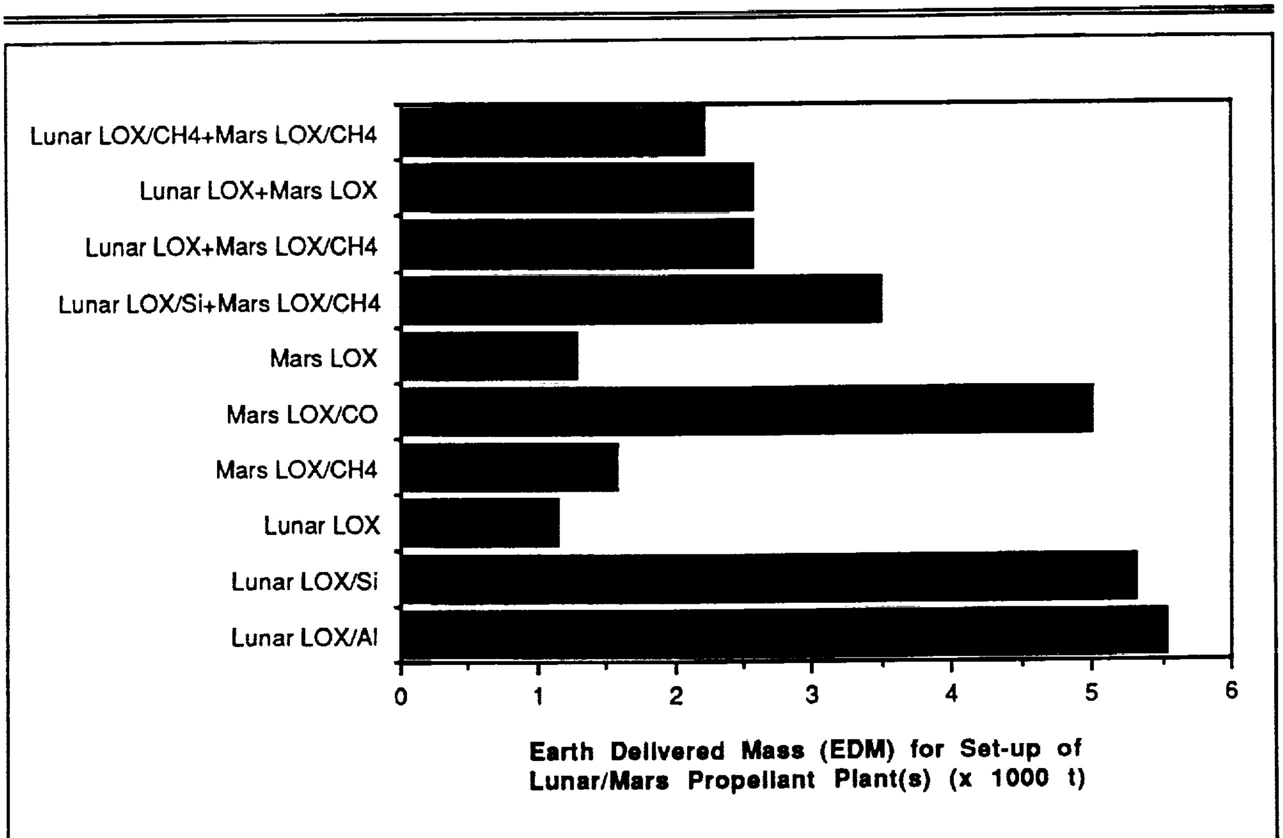


FIGURE 6-18: Earth Delivered Masses for Plant Setup

The second question to be addressed is "What are the potential benefits obtainable?" This question is answered by looking at a comparison of steady-state operation requirements summarized in Figure 6-19. The figure plots the ratio "without ISPP: with ISPP" for each case examined in this section. Since baseline (without ISPP) is the numerator, the higher the number, the better the performance gain with ISPP. The two cases that stand out in this comparison are Mars LOX/CO and lunar/Mars LOX/CH_4. Because Mars LOX/CO plant support requirements are relatively low, a high steady-state Earth-delivered mass ratio is realized. In the case where lunar and Mars LOX/CH_4 is used, this ratio is high because only plant support, the Mars mission payload, and the expendable stage used to boost the MTV with payloads to LLO from LEO need to be launched from Earth in the steady-state mode. These masses are lower, by a factor of about 2.5, than the round trip propellant mass with Mars mission payload for the case where no lunar or Mars propellants are used. Table 6-7 summarizes mass calculations by element for each case in Figure 6-19.

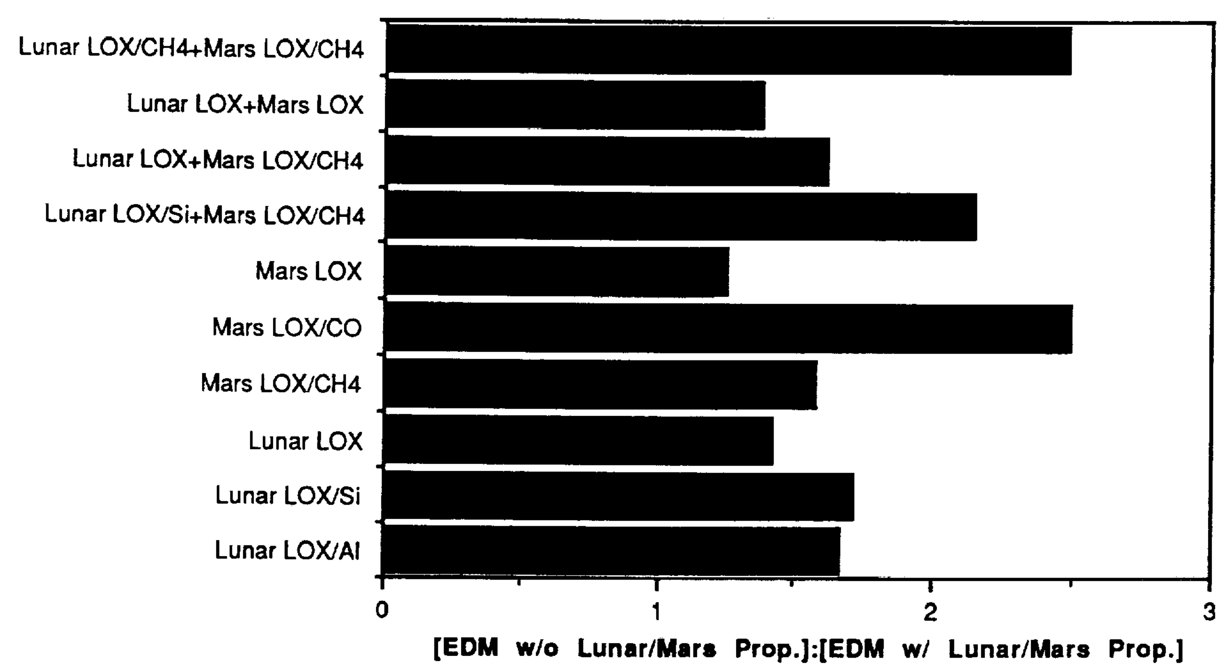


FIGURE 6-19: Comparison of Steady-State Operation Performance Gains

Since every case shows a value greater than one, just looking at steady-state results would indicate that any ISPP strategy is an improvement over the baseline. It is for this reason that many studies have suggested the use of various in situ propellants. The problem with only considering steady-state requirements is that the effects of establishing the propellant production plants and resupplying new transfer and excursion

TABLE 6-7
STEADY STATE ISPP ANALYSIS

Lunar produced propellant:	Baseline	LOX/Al	LOX/Si	LOX				LOX/Si	LOX	LOX	LOX/CH4
Mars produced propellant:	Case				LOX/CH4	LOX/CO	LOX	LOX/CH4	LOX/CH4	LOX	LOX/CH4
Mars mission payload	25000	25000	25000	25000	25000	25000	25000	25000	25000	25000	25000
MEV											
- dry	(12078)	(11805)	(12167)	(12078)	(33620)	(112507)	(29163)	(33620)	(33620)	(29163)	(33620)
- propellant (produced)		(140534)	(157377)	(27550)	(1147374)	(4819248)	(463479)	(1147374)	(1147374)	(463479)	(1147374)
- propellant (from Earth)	32133			4590			77246			77246	
- aerobrake	5789	13655	14980	5789	13147	16344	13739	13147	13147	13739	13147
MTV											
- core	(44736)	(45781)	(46036)	(45477)	(44445)	(46049)	(45287)	(44445)	(44445)	(45287)	(44445)
- drop tanks	51274	83324	95686	31848	39374	35430	45082	20461	17242	21420	14593
- prop. (produ…)		(3458656)	(3941431)	(574596)	(222412)	(456000)	(135246)	(939819)	(471620)	(564459)	(614940)
- prop. (from Earth)	1035412			95765	578633	380446	747362		41540	64404	
LEV											
- dry		(172597)	(198666)	(37997)				(42655)	(22844)	(26742)	(22670)
- propellant (produced)		(4436226)	(5194181)	(430835)				(994000)	(243219)	(302118)	(321571)
- propellant (from Earth)*				80884					40537	50353	
Expendable LOX/H2 stage											
- dry		28332	27864	31242				25240	28909	33754	22560
- propellant		454609	442860	527594				377051	469068	590588	309846
Lunar Propellant Production											
- production rat… (t/yr)		(4018)	(4646)	(517 O2)				(856)	(314 O2)	(394 O2)	(357)
- plant		(556481)	(457276)	(194000)				(83401)	(118000)	(148202)	(72129)
- hardware refurbishment		11130	9146	3884				1668	2353	2964	1443
- reagent resupply		73054	54658	1033				5035	626	788	0
Mars Propellant Production											
- production rate (t/yr)					(685)	(2637)	(299 O2)	(685)	(685)	(299 O2)	(685)
- plant					(56650)	(465019)	(17979)	(56650)	(56650)	(17979)	(56650)
- hardware refurbishment					567	4650	180	567	567	180	567
- reagent resupply					75339	0	0	75339	75339	0	75339
TOTAL MASS (kg):	1149608	689104	670194	807629	732060	461870	908609	543508	714328	880436	462495

* hydrogen tank mass included

#'s in () are not included in steady-state Earth launched mass requirements vehicles is not taken into account. When the plant set-up and vehicle change-out requirements are considered, many of the cases that show a benefit for steady-state operation will show only a minimal savings (or loss in the cases using lunar LOX/metal gels for the entire mission) in cumulative Earth-delivered mass, even when considering several Mars missions. The Earth-delivered mass savings (or losses) realized after 11 missions are summarized for all the cases in Figure 6-20. The two cases showing the greatest potential here are the lunar LOX with Earth-supplied hydrogen case and the case where both lunar and Mars LOX/CH_4 are used. The cases using lunar produced LOX/metal gels both required more than 2000 t additional Earth-delivered mass after 11 missions as compared to not using in situ propellant.

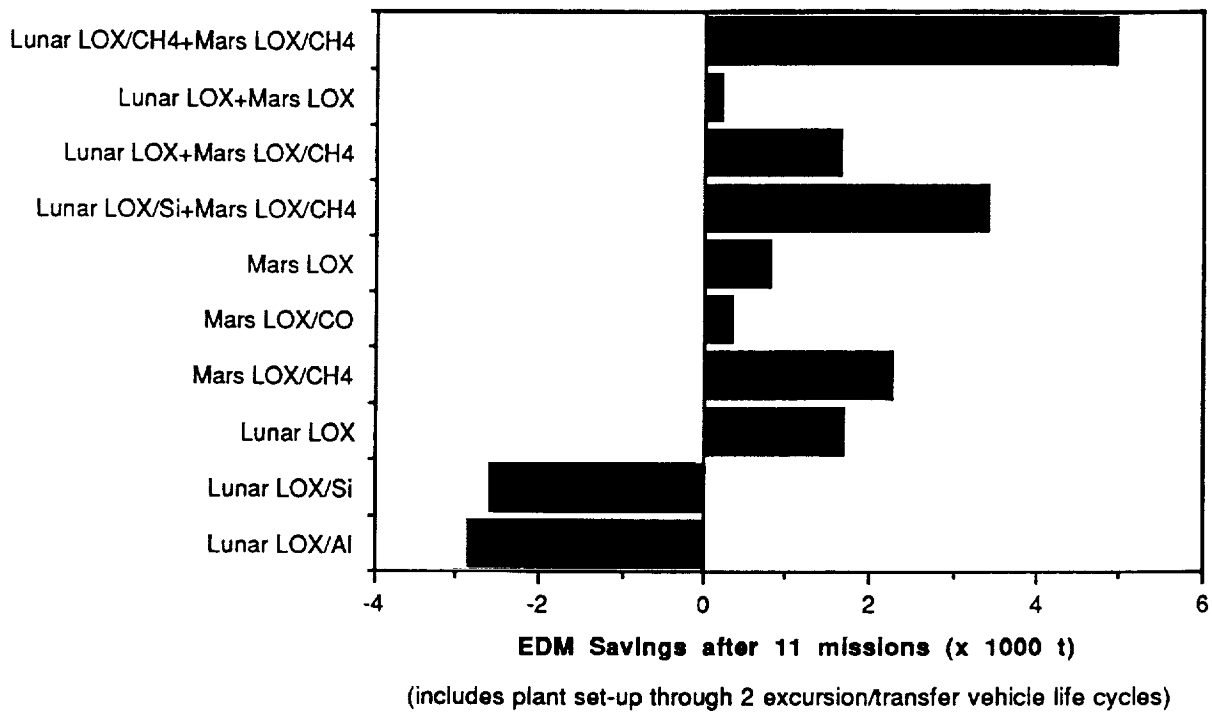
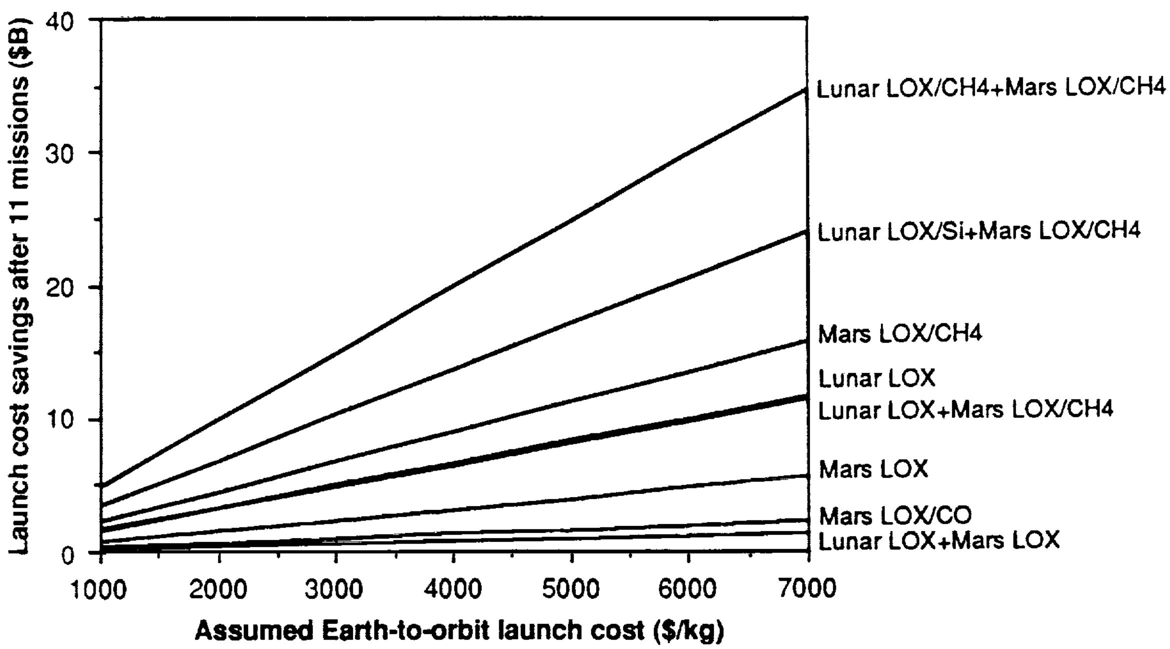


FIGURE 6-20: Earth-Delivered Mass Savings

Figure 6-21 translates the mass savings into Earth launch cost reductions for the eight cases with positive savings in Figure 6-20. For example, if Earth-to-orbit cost is \$5000 per kilogram, then manufacturing LOX/CH_4 on Mars for the return trip would save about \$10B over the 11 missions modeled in this study. This chart gives a preliminary indication of the order of magnitude of the ISPP development budget ceiling, but there are substantial uncertainties associated with several of the assumptions about the processes and their requirements.



NOTE: Lunar LOX/SI and LOX/Al do not offer launch cost savings after 11 missions and are not shown here

Figure 6-21: Potential Savings in Launch Costs

It is important to consider the effects of many of these assumptions made when comparing the results of these cases. For example, the assumption of five uses per vehicle is a strong driver of Earth-delivered mass savings over the course of many missions; a longer planned lifetime for these vehicles would improve all the results, but would probably also increase performance advantages of using ISPP. Many assumptions made concerning propellant plant requirements may change with better definition of the technologies, and with more operating experience at the Moon and at Mars. One key issue is the rate of hardware refurbishment, estimated to be 1% per year of total production system mass. Other factors, such as the rate of feedstock collection, may prove to be stronger drivers of the refurbishment rate than predicted here, especially for the lunar propellant production cases which require handling of thousands of tons of fine-grained abrasive lunar material per year.

7. DISCUSSION OF RESULTS

This study investigated several aspects of using ISPP techniques at the Moon and Mars to support round trips from Earth to Mars. The key question to be addressed was whether using propellants manufactured solely from in situ resources results in a net performance (and cost) advantage to a program of Mars exploration. The answer is a qualified "Yes"; the qualifications arise primarily from our limited knowledge of what is required to create and sustain a resource-intensive chemical manufacturing operation in a new environment. All but one of the candidate propellants considered in this study show significant steady-state performance gains over bringing all-chemical propulsion (LOX/H_2) from Earth; that issue is not in question. But the time to payback for the up-front investment in delivering and sustaining the production equipment is much less clear. A complete answer to this question will require better definition of the production process, its operational needs, and supporting elements.

Availability of Raw Materials. Using only commonly found raw materials in lunar regolith or martian atmosphere is a response to the lack of more detailed knowledge of the surface at either body. However, the resources that are easiest to locate may not always be the ones that lead to the best propellant candidates, the most efficient recovery and processing systems, or the smallest investment in plant setup and maintenance. The significance of this tradeoff is demonstrated in the performance and infrastructure assessments described in Sections 5 and 6.

Raw materials of interest are certainly available in lunar regolith. Oxygen is the largest elemental constituent of regolith, comprising 40-45% of the typical sample, independent of sample site. The most common metal oxide is SiO_2, at 40-50% by weight of the typical sample; elemental silicon comprises about 20% of most samples. Similarly, magnesium occurs at about 5% of the typical regolith sample. Abundances of the other metals considered -- iron, aluminum, and titanium -- are site-dependent, with titanium being the least common.

Although most of these elements are commonly found in lunar regolith, there are some issues to be addressed when considering their use in propellant manufacturing. Each element appears as a constituent in more than one regolith mineral. Oxygen is bound together with the different metals, and also occurs in the various mineral forms. So, although oxygen and the metals of interest are commonly found on the lunar surface, none is found in concentrated form. This means that the feedstock recovery and processing scheme will have to be designed to match the availability of raw materials; maximizing process efficiency or minimizing resource consumption would be secondary objectives. In bulk, the regolith material is a blanket of very fine-grained particles, varying in size from millimeters to micrometers. Whereas most processing on Earth begins with a stock that can be sized to meet other process design constraints, lunar process designs must make another concession to the lunar environment.

One possible answer to these concerns would be "prospecting" the Moon to discover any concentrated rock deposits of particular minerals. Concentrated mineral feedstock could lead to a more efficient, less constrained process and plant design. However, there is no firm evidence of any such ore deposit on the Moon; prospecting the surface could require completing an extensive, time-consuming survey phase before a permanent processing base and its associated infrastructure could be delivered and brought on line. The survey might require samples to be returned to Earth for assay. Moreover, the complexity of such an operation far exceeds sample selection and collection of the sort planned for automated planetary sample returns; there is at least a strong possibility that human explorers would be required to conduct critical portions of such an operation. The implication for SEI planning is more time and resources expended early in the program, before an ore deposit, yet to be discovered, could be exploited.

Volatile elements deposited in lunar regolith by the solar wind are another potential resource for propellant manufacture from in situ resources. The advantages of using this resource are that higher performance liquid bipropellants could be recovered, and that the same propellants could be manufactured at all three terminus points: Earth, Moon, and Mars. However, gas concentrations are diffuse, requiring that very large amounts of bulk regolith be handled and processed to recover adequate quantities of volatiles. The gases exist, but using this resource will require advanced technology to solve several key issues.

At Mars, likely first candidates for locally-derived propellants are CO and CH_4, if only because of the ubiquitous CO_2 atmosphere. The C and O components can be readily extracted using simple processing methods. Hydrogen for the methane combination could be brought from Earth, or possibly recovered from martian permafrost in certain locations (more exploratory results are required to confirm this possibility). Choosing the bipropellant LOX/CO, with a lower specific impulse but recoverable entirely from local resources, may be a good trade in return for a smaller investment in the surface chemical plant and a continuing resupply of hydrogen that would be required for LOX/CH_4.

Processing Options. Several processing options have been proposed to use the resources known to be commonly available at the Moon and Mars. Some of these methods draw on well-developed processing experience on Earth, while others use novel approaches proposed specifically for an extraterrestrial environment. Terrestrial mining and resource extraction methods use readily available reagents to expedite processing efficiency or to reduce cost; on Earth, the abundant supplies of oxygen, hydrogen, carbon, and water are used extensively in chemical processing. Because these resources are not readily available on the Moon or Mars, even the processes derived from terrestrial experience must be modified to conserve these and any other reagents delivered from Earth. The importance of this point becomes apparent when infrastructure requirements are considered (Section 6).

Other methods have been proposed that do not require reagents; instead, these methods use relatively greater amounts of thermal or electrical energy to run the process. These processes could be considered "space-based": they are not the most economical choices for processing on Earth, but they may offer advantages in space, where energy is more readily available than reagents. Experience with these processing candidates is very limited; for the lunar option, high temperature materials technology advances are likely to be required even to make tests in a relevant environment. Because proof of concept tests have yet to be completed for these approaches, they must be considered more speculative than other options.

We have reviewed many candidate processes for manufacturing on the lunar surface looking for a process that is:

- of a robust, simple design,
- energy efficient (or at least that doesn't require very large quantities of thermal or electric energy for sustained operation),
- able to recover adequate amounts of both oxygen and a desirable metal, and;
- well-defined in terms of its requirements.

Although this seems like a wish-list of desirable qualities, each item has implications for supporting infrastructure needs and for overall performance gain. A simple design is usually associated with reduced operations and maintenance requirements. The HF Leach process (refer to Figure 3-9 for a simplified version) appears to require many steps to produce the desired end products, and to recover the HF reagent. Complex processes may require increased maintenance and operator intervention.

Energy demands that exceed planned SP-100 reactor-based capability could require substantial enhancements to the surface power system. Selective ionization is an example of a process that would require very large amounts of energy for regular operation. The solar wind gas extraction concept presents a different challenge; although energy needs per unit fuel production are comparable with many other candidate processes, the energy source must either be carried on a large miner vehicle, or must be beamed to the miner, since processing the large amounts of regolith to drive this process would be impractical for a fixed central location.

Propellant production must be matched to the interplanetary transfer requirements, and the plant's output must be balanced to deliver sufficient metal and oxygen for the desired mixture ratio. Figure 3-22 of Section 3 indicates the effect of mixture ratio on expected plant mass to produce propellant quantities that are typical for the Earth-Mars transfer. Ilmenite reduction, often discussed as a leading candidate for obtaining oxygen, recovers only a small amount of the oxygen available in regolith; this built-in inefficiency leads to increased feedstock collection and beneficiation requirements to produce the quantities of oxygen needed for Earth-Mars propellant. Moreover, this process can separate only one metal, iron, which has been shown to give inadequate performance because of its low specific impulse.

The final point -- clear definition of plant sizing and requirements -- appears on the list because of the preliminary nature of all the design concepts proposed. Estimates for plant physical parameters (mass, volume, etc) are not yet well understood; refurbishment needs and expected equipment life cycles are largely unstudied. An assessment of the type conducted in this study requires that the candidate processes be understood well enough to answer these basic issues. Yet, we find that very little firm information exists. The resulting performance calculations understandably have large expected errors.

With this preliminary level of definition, it is unrealistic to select one process best suited to recovering each candidate propellant. Instead, we opted to make loose characterizations of groups of processes to determine mass, power needs, refurbishment, etc. for each propellant. What can be concluded from this approach is that certain propellants are not likely to offer performance gains. Titanium is the least abundant metal found in regolith minerals, and the titanium dioxide bonds are difficult to break; only two processes have been identified that might do the job. Therefore, titanium is an unlikely candidate for use in propellant manufacture. The combination of aluminum and magnesium together would probably require two separate processes to recover the different metals; this requirement suggests that LOX/Al-Mg would not be a good candidate to pursue, unless a way could be found to reduce the expected burden of installing and maintaining two separate processes.

Of the remaining metal candidates, iron, silicon, and aluminum, silicon is by far the most abundant; aluminum seems to be concentrated in the lunar highlands. Iron is available, but the low specific impulse of LOX/Fe eliminates this combination from serious consideration. What is required to further explore potential use of silicon or aluminum is better definition of the candidate processes that could recover these metals, together with study of the beneficiation steps to be performed on bulk regolith. The entire operation of beneficiation, processing, storage, and transfer should be defined and evaluated to improve understanding of the plant and its associated infrastructure.

Performance and Infrastructure Assessment. Mass performance calculations for a single Mars mission (assuming that the plant and its support systems are installed and in full production) offer further justification for eliminating some of the lunar propellant options. LOX/Al-Mg shows essentially no difference in performance over LOX/Al, so there seems to be little motivation to carry an option that requires more surface processing. Titanium's lower specific impulse (20-30 sec less than aluminum or silicon) when combined with oxygen produces higher mass requirements, even though the higher density of LOX/Ti reduces propellant tank masses. Given the difficulty of recovering titanium, a LOX/Ti monopropellant can also be eliminated from consideration. Similarly, iron is eliminated because of the much lower Isp (195 sec) of LOX/Fe, which leads to the only performance result that is worse than the baseline.

We found the predicted performance of LOX/Al and LOX/Si propellants to be nearly equal for single missions, as suggested by their nearly equal specific impulses. The density of LOX/Al is somewhat higher, indicating smaller, lighter propellant tanks would be required. However, both the lunar propellant plant for recovering LOX/Al and the delivered support items (refurbishment hardware and reagents) are estimated to be about 20-25% more massive than the LOX/Si support. Therefore, a multi-mission comparison of these alternatives suggests that LOX/Si would be easier to support in the long run.

Given the greater abundance of silicon on the Moon, this seems to point in favor of using LOX/Si over LOX/Al. However, the uncertainties in plant masses, definition of support needs, feedstock beneficiation, and on-going refurbishment makes this too close to call until better definition is available. Moreover, neither of these candidates appears to offer an advantage if used by itself for the entire Earth-Mars round trip (reference Figures 6-6 and 6-7). The reason is that propellant manufactured on the Moon for the return trip from Mars must be carried through the outbound impulse sequence, thereby raising the propellant requirements for the outbound leg. If lunar propellant is used for just the outbound leg, and coupled with a Mars-based propellant for the return, the performance picture improves dramatically. The example presented in section 6 combines lunar LOX/Si with martian LOX/CH_4 to yield an early payback, and reduction in mass delivered from Earth of over 3,000 t.

Following this approach, using LOX/CH_4 from both the Moon (outbound) and Mars (return) gives even better performance, since the specific impulse of this combination is superior to any of the metallized monopropellants. The big question here is whether methane production from solar wind gases bound in the lunar regolith is truly feasible.

This analysis of infrastructure requirements for the various propellant combinations indicates that the performance gain for a single mission is not, by itself, sufficient to characterize the benefit of using a particular in situ propellant. Instead, it is necessary to develop a comparison approach, such as the one presented in this study, that accounts for the "life cycle" of plant delivery, setup, operation, and refurbishment over several missions.

One of the clearest demonstrations of this point is illustrated in Figure 6-19 of the previous section. Using Mars LOX/CO for the return trip, coupled with LOX/H_2 from Earth for the outbound trip shows excellent steady-state performance potential: the ratio of Earth-supplied masses of baseline:LOX/CO is about 2.5:1. The performance is good because plant support requirements are low. On the other hand, although the performance of LOX/CH_4 is much better than LOX/CO, we assume that hydrogen must be brought from

Earth, making this case less attractive in steady-state comparison. However, the situation reverses when plant setup requirements are included (refer to Table 6-6 and Figure 6-20 for details). The plant mass to produce LOX/CO is greater than that for LOX/CH_4 by nearly a factor of ten because the process requires a large refrigeration mass to operate. So, the single mission advantage for LOX/CO becomes a long-term advantage in favor of LOX/CH_4 production at Mars.

Some workers have suggested that just recovering oxygen to be combined with hydrogen from Earth would capture most of the performance gain of ISPP. We examined three such cases: lunar LOX only, Mars LOX only (just for the return trip), and both lunar and Mars LOX. Of the three, the lunar LOX-only case is the only one to show a clear advantage for ISPP use over several flights. Note that each of these applications is different, so comparisons of these cases must be done carefully. Assuming that the plant and support requirements don't change with improved definition of these elements, lunar LOX production could serve as the first step in an evolving strategy of increasing use of in situ resources. However, using martian resources should probably not be limited to just LOX recovery.

SEI Architecture Impact. Single mission performance estimates were made for several different transportation architectures, depending on where propellant manufacturing took place. For all scenarios that manufacture lunar propellant for use in the Mars Transfer Vehicle, there are three options for flight profile. We concentrated much of our attention on the "3-leg" profile, using LOX/H_2 from Earth for the Earth-Moon trip, staging and refueling the MTV from low lunar orbit with lunar-produced propellant. The return trip from Mars (using either lunar or martian propellant) ends in low Earth orbit, where the MTV is refurbished. From a performance standpoint, this approach seems to be preferable to the commonly discussed alternative of having a lunar freighter move manufactured propellant back to LEO to fuel the MTV there. Another alternative would be to base the MTV in low lunar orbit exclusively, leaving from and returning to a transportation node in lunar orbit. (The node might also be stationed at a libration point.)

Regardless of the option, use of lunar resources for MTV propulsion will impact the overall SEI transportation architecture. The 3-leg profile assigns all transfer propulsion to the MTV, so vehicle design would have to reflect the greater use of staging. However, it may be possible to transfer propellant or tanks in LLO at the Moon without establishing a transportation node for that purpose. The other two mission profiles appear to have a greater impact on the architecture. To base the MTV in low lunar orbit would require a vehicle to shuttle Mars-bound crews and payloads to LLO, together with an orbiting node to serve as a staging area. The shuttle function could probably be handled by extra flights of the LTV, but the node in LLO would be a new facility. Even the LEO-to-Mars-to-LEO option would require a tanker to ferry propellant from LLO to LEO to load the transfer vehicle.

The impact on the SEI architecture of using lunar resources will be on some or all of three areas: Mars Transfer Vehicle design, transportation node location and number, and the need for shuttle/ferry vehicle flights between Earth and Moon. There are also operations and support considerations for any new elements introduced, whether they are orbiting nodes or additional flight requirements.

Recommendations. The infrastructure assessment approach derived in this study seems to be a valuable way to "take the long view" of using in situ resources for propellant manufacture. The analysis method can certainly be further refined, to lead to a tool that will be useful in deciding which propellant combinations should be manufactured, and by what means. However, the most valuable activity for the near term would be to substantially improve the definition of candidate processes, beneficiation steps, and their support and refurbishment needs. Without a clearer, more accurate statement of these requirements, no amount of analytical work will resolve the questions surrounding how best to proceed to bring in situ propellant production closer to implementation.

APPENDIX A: DATA SOURCES FOR LUNAR SAMPLE ANALYSIS

Tables on the following page identify the sample characterizations used to derive average oxide and elemental abundances for regolith and basaltic rocks at Apollo and Luna landing sites. A bibliography of source material, organized by mission, is also included in this appendix.

TABLE A-1
LUNAR SAMPLES FOR SITE CHARACTERIZATION

MISSION	LUNAR SAMPLE
Apollo 11	10069, 10071, 10044, 10057, 10084, 10017, 10072, 10020
Apollo 12	12009, 12004, 12022, 12070, 12001, 12057, 12018, 12021, 12040, 12051
Apollo 14	14163, 14003, 14240, 14073, 14310, 14072, 14053, 14259, 14421, 14148, 14156, 14149
Apollo 15	15016, 15058, 15076, 15256, 15499, 15555, 15556, 15415, 15418, 15021, 15101, 15271, 15301, 15471, 15501, 15601
Apollo 16	60004, 65785, 60666, 60615, 60618, 65795, 60635, 60639, 66095, 60315, 62235, 61156, 68415, 67955, 61016, 67075, 61295, 68815, 63335, 60600, 61220, 61241, 61501, 64421, 65701, 66041, 66081, 67480, 67600, 68842
Apollo 17	74255, 74275, 75075, 70017, 71569, 71055, 70215, 75035, 75055, 70035, 72435, 72275, 76315, 77135, 76055, 78155, 77017, 76230, 72415, 79135, 74220, 75061, 71041, 71501, 75081, 71061, 70161, 74240, 70181, 74260, 79221, 79261, 78501, 76501, 72501, 72701, 73141
Luna 16	
Luna 20	22012, 22013
Luna 24	24077, 24109, 24149, 24174, 24182, 24210

TABLE A-2
ADDITIONAL SAMPLES FROM THE HANDBOOK OF LUNAR SOILS, 1983

Apollo Mission	Regolith Sample Number
Apollo 11	10002, 10010, 10084
Apollo 12	12001, 12003, 12030, 12032, 12033, 12037, 12041, 12042, 12044, 12057, 12060, 12070
Apollo 14	14003, 14148, 14149, 14156, 14163, 14240, 14259, 14260
Apollo 15	15012, 15013, 15020, 15040, 15070, 15080, 15090,15100, 15210, 15220, 15230, 15250, 15260, 15290, 15300, 15400, 15410, 15420, 15430, 15470, 15500, 15510, 15530, 15600
Apollo 16	60050, 60500, 60600, 61140, 61160, 61180, 61220, 61240, 61280, 61500, 62240, 62280, 63320, 63340, 63500, 64420, 64500, 64800, 64810, 65500, 65700, 65900, 66040, 66080, 67460, 67480, 67600, 67700, 67710, 67940, 68120, 68500, 68820, 68840, 69920, 69940, 69960
Apollo 17	70011, 70160, 70180, 71040, 71060, 71500, 72140, 72160, 72320, 72440, 72460, 72500, 72700, 73120, 73140, 73220, 73240, 73260, 73280, 74120, 74220, 74240, 74260, 75060, 75080, 76240, 76260, 76280, 76230, 76500, 77530, 78220

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