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AN ANALYSIS OF POSSIBLE ADVANCED SPACE STRATEGIES FEATURING THE ROLE OF SPACE RESOURCE UTILIZATION†

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Abstract—A major weakness of space planning in the U.S.A. has been the lack of clearly defined, major space goals within a coherent, politically palatable, long-range national space strategy. Unresolved issues include the Space Station's role, the most profitable space exploration strategies, and space resource use. We present an analysis of these factors with special emphasis on space resource utilization. Our performance modeling reveals that lunar oxygen is useful on or near the Moon and—if lunar hydrogen is available—lunar oxygen is also economical in LEO. Use of volatile materials from Phobos/Deimos is preferred or attractive in LEO, low lunar orbit, and—if lunar hydrogen is unavailable—on the Moon. Thus it appears that resource synergisms between operations in the Mars system and in Earth–Moon space could become commercially important.

1. INTRODUCTION

A major weakness of space planning in the U.S.A. has been the lack of clearly defined, major space goals within a coherent, politically palatable, long-range national space strategy. These space goals must help satisfy the nation's needs for new technology development and the acquisition of new scientific knowledge. The goals should also embrace the important psychosocial need to explore and ultimately colonize new worlds, and should provide a significant potential for economic return. Ideally, these major national space goals would be synergistic with those of other nations.

The declaration of a new National Space Policy by President Reagan and its confirmation by President Bush (featuring possible lunar bases and manned Mars missions) as well as likely approval of significant funding for a multiyear NASA program to develop the "Pathfinder" technologies required for this aggressive space program, constitute important progress toward the large-scale human exploration and utilization of space beyond LEO.

However, several fundamental and important issues remain unresolved, including: (1) the role of the U.S. Space Station in this endeavor; (2) which strategies for the human colonization of space (i.e. which post-Space Station space goals) possess the "best" package of attributes; (3) whether the use of space resources (from the Moon or elsewhere) has economic, operational, and/or strategic advantages over totally relying on Earth-based materials; and (4) the most productive way to maximize international cooperation in these momentous space ventures.

In this paper we present an analysis which provides a useful method of organizing one's approach to understanding and assessing this complex matrix of space alternatives, and also constitutes a convenient planning tool for corporations, organizations and countries that are interested in having the ability to forecast events in the future human development of space.

One conclusion of this analysis is that space resource utilization emerges as a pivotal development in the evolution of large-scale human operations in space. It is a critical decision point because the absence of inexpensive space materials and supporting technologies can preclude or significantly delay any significant human exploration and utilization of space.

Our recent studies [1] of lunar oxygen production for use near the Moon and in LEO demonstrate that the potential economic benefits (vs using oxygen from Earth) are marginal-to-promising depending on which assumptions (e.g. relation between plant productivity and mass) are adopted. One problem in this scenario is the lack of an economical source of hydrogen on the Moon.

The suggestion [2] that volatile materials (e.g. H, C, and N) abundant on the moons of Mars (Phobos and Deimos: Ph/D) might be efficiently transported to the desiccated lunar surface and markets elsewhere in the Earth–Moon system (including LEO), has been subjected to a preliminary feasibility and economic analysis.

It appears that volatile-rich chondritic materials—ostensibly abundant on Ph/D—can be used for *in situ* propellant production near Mars [3]. Our preliminary

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cost analysis (based on our OTV study data) suggests that the delivery of 500 klb of Ph/D materials to a lunar base can save $0.8 B per flight over the Earth–Moon loop. Further, in Lunar-emphasis scenarios, the retrieval of Ph/D-derived hydrogen to the Moon could contribute to the economic use of lunar oxygen in LEO.

Therefore, resource synergisms between operations in the Mars system and in Earth–Moon space could become commercially important. A significant space economy using lunar and Martian resources early in the 21st century is possible, although some assumptions about available technologies and possible space markets introduce uncertainties into our results. Significant operations cost benefits would result whenever Ph/D materials (e.g. methane, water) are transported to the Moon or even LEO, as opposed to similar resource supply loops originating on Earth. Thus, the potential economic incentive for the human exploration of Mars could be significant.

In the nearer timeframe, the U.S. Space Station's potential roles in human explorations of deep space are important [4]. If Space Station Freedom is utilized as a deep space mission transportation node—as originally envisioned by Von Braun and other seminal thinkers (and as usually assumed in studies of lunar oxygen economics)—it would provide a convenient departure and return point for Lunar and Martian astronauts and cargoes. The Station would also be used to store *or* process materials from Mars and/or the Moon into propellants or other profitable commodities.

The question remains, however, are these uses of the Space Station compatible with presently foreseen scientific endeavors?

The above discussion is considerably expanded and further quantified by the results presented in this paper. We first present a general, semi-quantitative analysis of the "big-picture" issues related to the future use of space resources. Then, we transition into a quantitative discussion of lunar and Mars resources, featuring performance and some economic data.

2. SPACE FUTURES ANALYSIS

We utilize a decision tree analysis in which the major questions and their alternatives are identified and appropriately positioned on the diagram. Using our analysis of the appropriate data (including engineering, political and scientific factors) we assign probabilities to each decision point along the tree. Thus for each track along the diagram (i.e. set of decisions culminating in a specific outcome) we can calculate cumulative probabilities of occurrence. The relative values of these final probabilities are indicative of which combinations of events are more likely to occur in the future. The final decision tree is in spreadsheet form and thus sensitivities of the final probability to uncertainties in any individual decision probability can be ascertained.

A typical approach to this type of high-uncertainty problem is to utilize a Delphi poll in which numerous individuals with special expertise in the policy and technical areas of interest provide estimates of the probability of occurrence of individual events at each branch point. However, in this paper we have chosen to simply illustrate this technique for the problem of space futures by showing two rather different estimates of probable futures (Figs 1 and 2). Discussions of the major issues associated with each decision branch point appear below.

2.1. A major space venture in the next 20 years

We believe it is highly probable that a major space venture will occur in the next 20 years. The issues which positively influence this opinion include the following points:

- The U.S. budget situation must be rectified relatively soon (e.g. within a decade). In the current deficit situation it might be politically difficult to initiate a large expensive space venture. The solution to this budget challenge is courageous political leadership at the Presidential and Congressional levels; Presidential leadership will also be required to develop support for human missions to the Moon and planets.
- The U.S. is emerging from a fairly dormant period in its space program. Indeed, since the termination of the manned Apollo program in 1972 until the last few years, little planning of major manned lunar/planetary ventures has been funded or accomplished by NASA. With the encouragement of President Bush and (hopefully) his successor, plus the grass-roots support of most of the U.S. population, we feel the time is right for bold space adventures.
- Soviet, European and Japanese technology and space activities are rapidly improving and could expand to the point that the U.S. space program is clearly not in a leadership position; this would probably become politically unacceptable in the U.S. and stimulate action.
- Competition and/or cooperation with the Soviet Union will be increasingly viewed in the U.S. as the only acceptable alternatives (doing nothing will be politically untenable). If Soviet–American relations continue to improve, a joint Soviet–U.S. manned Mars mission is an attractive option. We believe the United States' participation may not be absolutely essential to the human exploration of Mars.
- The Space Shuttle will eventually (we hope relatively soon) be turned over to a purely operational launch agency (as opposed to NASA which is an R&D organization). This will free NASA to pursue its original goal—the exploration of the solar system—and NASA again will be fully able to address the challenge of establishing human outposts on the Moon and Mars.

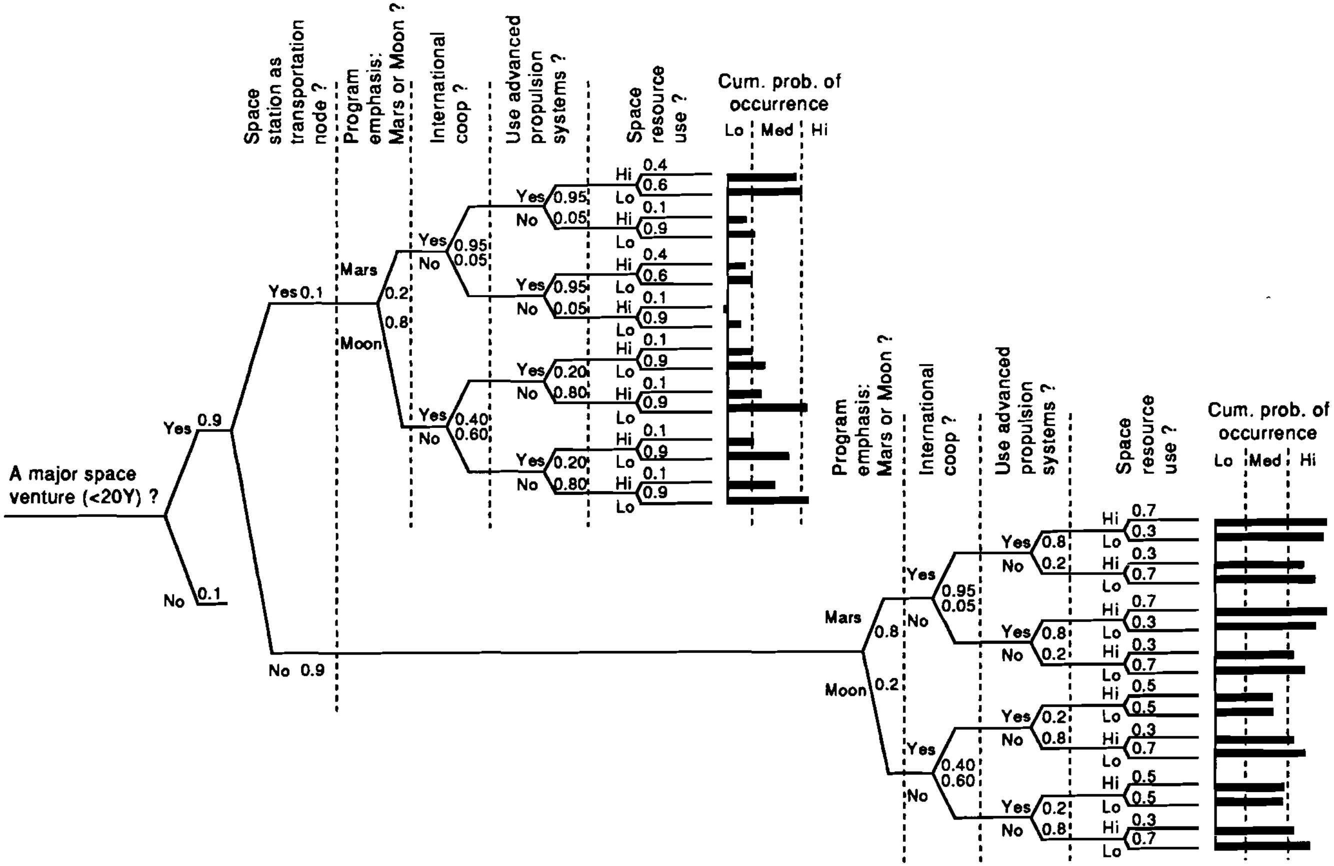


Fig. 1. Space futures probability tree—case 1.

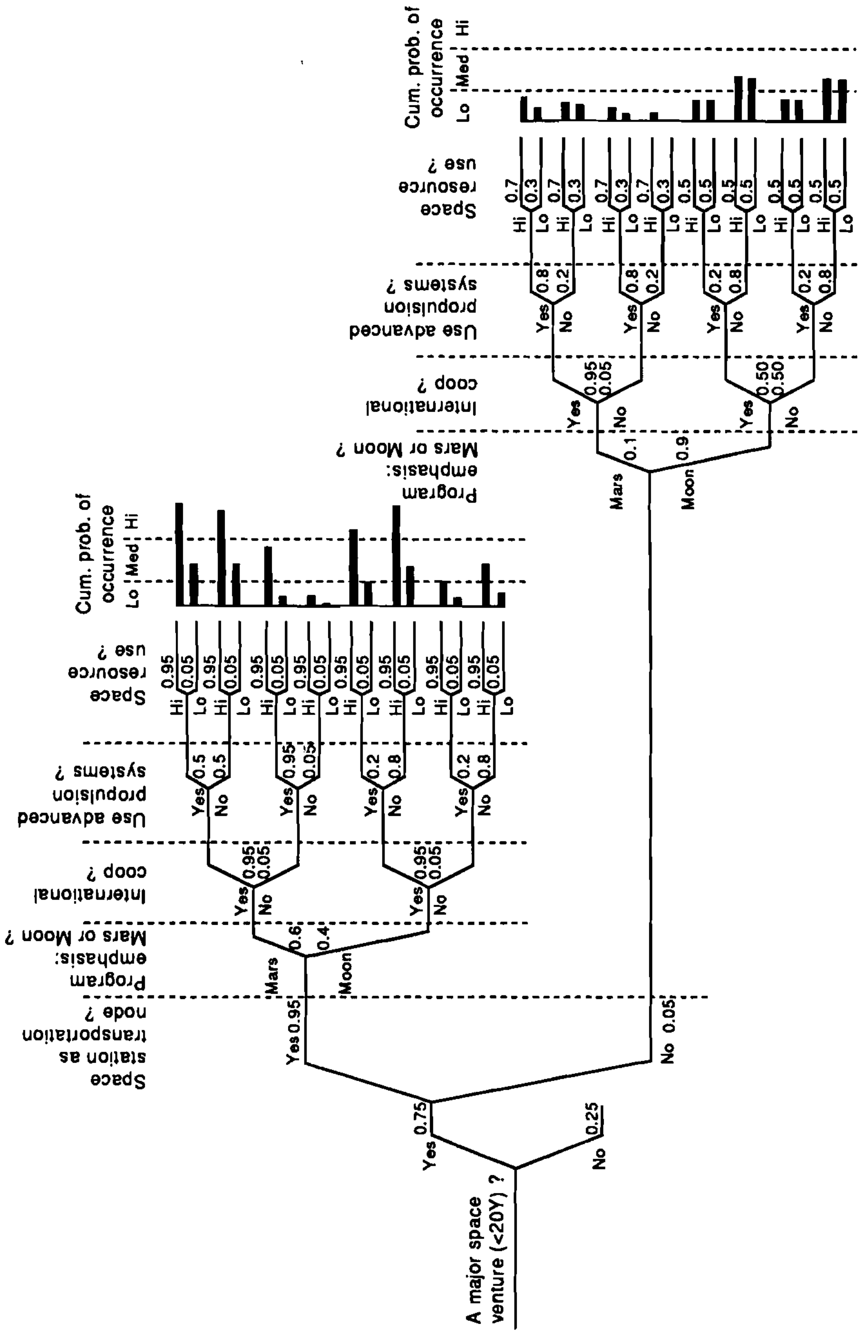


Fig. 2. Space futures probability tree—case 2.

- The thirst for scientific knowledge will finally coalesce internationally and provoke nations to attempt to form international management organizations directed toward human exploration and utilization of the Moon and planets. Allied with this is the growing realization that dwindling resources, pollution, and opportunities for international conflicts could be reduced by a more unified global approach which redirects national energies and resources away from conflict-oriented activities and toward utilization of the immense, untapped energy and resource wealth available on the Moon and Mars.
- It is quite possible that technological breakthroughs (e.g. in nuclear propulsion) may make the human exploration of Mars and the solar system more feasible and affordable than they appear to be today.

2.2. Space station as a transportation node

Human missions to the Moon and Mars will require a facility in LEO where Lunar or Mars Vehicles can be assembled, fueled, launched, and (at mission conclusion) retrieved [4]. The probability of the Space Station Freedom, as currently envisioned, being used as a transportation node for any major space venture is very low. The reasons include:

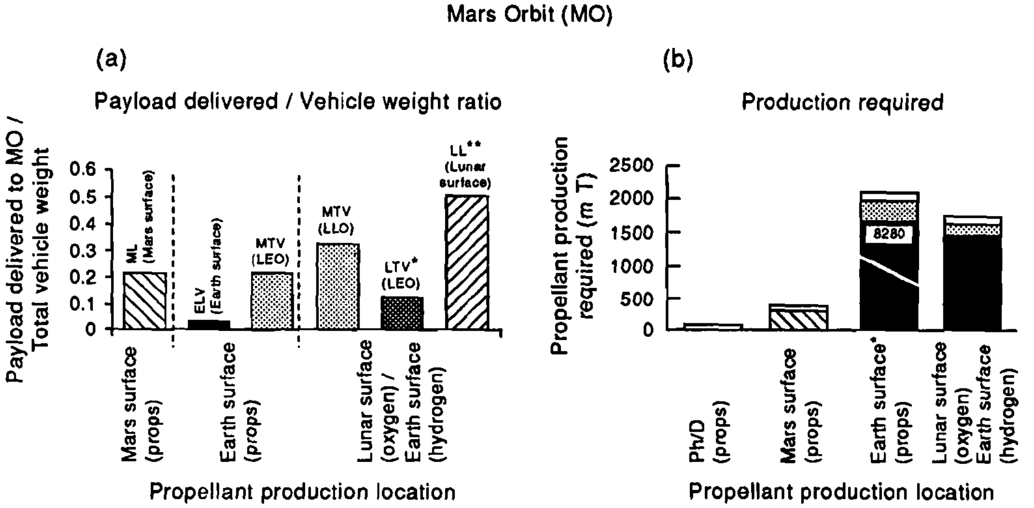
- The present Space Station is not well designed from a transportation standpoint, will be very expensive and will serve primarily as a scientific and experimental test base; its role in any long term space transportation infrastructure is very limited.
- Safety considerations will not allow the required large quantities of propellant to be stored on a permanently manned space facility.
- The scientific experimentation to be performed on the Station is totally incompatible with docking of orbital transfer vehicles (OTVs) transfer of propellants, handling of large payloads and other operations which would disturb the microgravity environment.
- Dynamic control complexities associated with a transportation facility attached to the presently planned Space Station will be formidable, particularly when very large payloads are attached and removed.
- The scientific community will not tolerate the contamination and interference a space transportation base would introduce to the Station.
- The international community (e.g. ESA, Japan) might feel that transforming the Station into a transportation node would threaten their investment in the program.
- A separate transportation node can probably be constructed nearly as inexpensively as attaching the node to the Station, if appropriate use is made of Space Station hardware and systems.
- The transportation base could be man-tended from the Station on an as-needed basis and generally be only controlled remotely from the Station.
- Scientific payloads could be returned to the transportation node from the Moon or Mars and brought to the Station by the orbital maneuvering vehicle (OMV) for processing.
- Soviet involvement in the transportation base is quite conceivable; having a separate facility would ameliorate any proprietary or military issues which might arise.

2.3. Program emphasis: Mars or Moon?

We believe that Mars will be the emphasis of any major U.S. space venture in the next 20 years unless there is no significant development of a LEO transportation node. Many of the reasons for this stem from the fact that Mars is much more Earth-like than the Moon. The following is only a brief summary of supporting comments.

- The potential scientific bonanza on Mars—in geoscience, meteorology, and possibly biology—easily dwarfs that of the Moon. Plus the detailed geochemistry of Mars' surface is much less well specified than the Moon's and thus there is much more to learn.
- Because of the presence of an atmosphere, significant amounts of water, a $1/3\,g$ surface gravity field, and a surface environment quite reminiscent of Earth (for an extraterrestrial site Mars is *very* Earth-like), Mars seems very suitable for *in situ* resource utilization (ISRU) and the eventual independence of any Martian outposts from Earth.
- The moons of Mars (Phobos and Deimos)—because of their proximity to Mars, great accessibility from Earth, and potential for *in situ* propellant production—offer the opportunity to extend at an early time, with relative ease, the inner solar system space infrastructure out to the vicinity of Mars. This would open Mars, the asteroids and the entire outer solar system to eventual human exploration
- Mars has an attraction far surpassing the Moon in the minds of the public as a place for human exploration and colonization. This is particularly true for today's young people for whom the colonization of Mars can serve as a motivational beacon for their daily educational and research activities.
- Mars is the most likely target for joint Soviet–American manned expeditions.

Regardless of the overall program emphasis, we do not expect either the Moon or Mars to be neglected by humans. However, neither do we think it inevitable that significant developments on the Moon must precede the large-scale human exploration of Mars. In fact, considerable synergisms may exist



* Delivers hydrogen from Earth to LLO
** Delivers lunox to LLO

* Actual contribution of ELV is 5 times larger

Fig. 5. (a) Delivery to Mars orbit. (b) Production for Mars orbit.

In Fig. 4(a) and (b) the clear winner is Ph/D over the Earth as a source of propellants or hydrogen for the lunar surface, assuming only a moderate or negligible lunar oxygen production capability exists. It is interesting to note that the PTL and LTV ratios [Fig. 4(a)] for the Ph/D and Earth hydrogen scenarios are almost identical. This is because of the similar delta *V*s between the LEO–LLO and Ph/D–LLO loops (we assume aerobraking at appropriate locations). However, notice also that the PTL ratio for the hydrogen scenario is about 8% larger than for the propellant delivery scenario. This is a function of the fact that both vehicles must deliver the same propellant payload (100 mT) to the lunar surface but in the hydrogen case the PTL is not required to carry the oxygen for the lunar lander.

3.3. Mars orbit

Figure 5 refers to Mars orbit as the site of propellant delivery. Figure 5(a) shows ratios for propellant production sites including Mars surface, Earth, and a lunar oxygen scenario. We include the Mars orbit case to illustrate the relative performance of each of the above three scenarios assuming no significant *in situ* propellant production infrastructure has been established at or near Mars.

In Fig. 5(a), for the lunar oxygen case, propellants are actually originating in two locations: the Moon (lunox) and the Earth (hydrogen). This necessitates an LTV to deliver hydrogen to LLO to drive the LL, the MTV, and provide hydrogen propellants (to accompany the lunox) in Mars orbit. Thus, while the

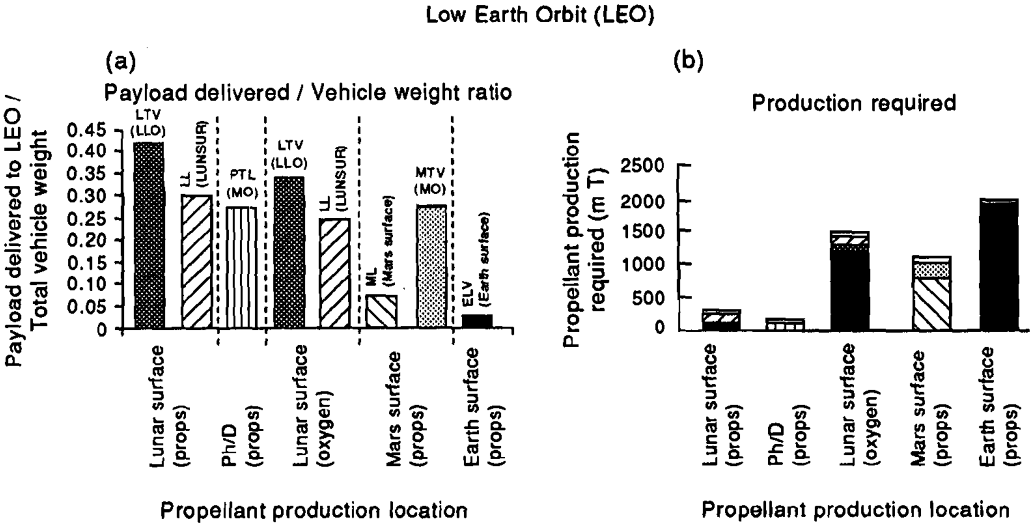


Fig. 6. (a) Delivery to LEO. (b) Production for LEO.

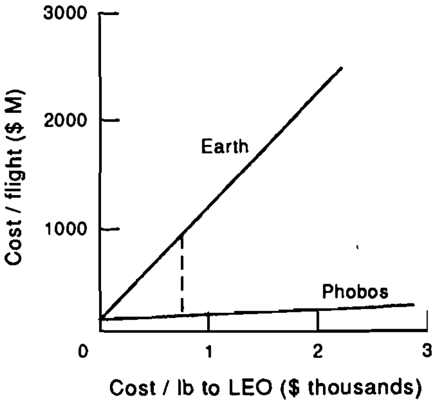


Fig. 7. Earth and Phobos scenario sensitivity to ELV costs.

LL appears to have a high payload/vehicle ratio this is deceptive because only the oxygen is delivered to LLO by this vehicle. The LTV is not really delivering terrestrial hydrogen from its source (Earth) and thus the actual ratio for hydrogen is represented by the ELV bar for the Earth Surface case. It is clear, however, that Mars surface is preferred to Earth.

Figure 5(b) conclusively favors the Mars surface for delivery of propellants to Mars orbit over the lunox/Earth H scenario. This is largely because the ELV requires large amounts of propellants to escape Earth's huge gravity well.

3.4. Low Earth orbit

Figure 6 shows deliveries to LEO from Ph/D, the lunar surface, Mars surface, and Earth. The payload/vehicle ratio shows that Ph/D is the preferred location for deliveries to LEO although the lunar surface is competitive. Mars' and Earth's surfaces lag behind as usual. Even without including the ELV propellants required to deliver the lunar lander hydrogen to LEO, the Ph/D scenario is more efficient than lunar oxygen. Thus it appears that the moons of Mars actually may have the potential to efficiently supply LEO with propellants, water and other materials.

It is interesting to compare the performance results for Ph/D resource scenarios with those of other production sites. In the LEO and (of course) Mars orbit cases it is the winner, in the lunar surface case it is the non-lunar winner, and it is very competitive in the LLO case, particularly if H is unavailable on the Moon. This suggests strongly that *early* development of the Martian moons is a strategy with important positive implications for operations not only near Mars, but in the Earth–Moon system.

3.5. Phobos/Deimos economic benefits

We have performed a preliminary economic analysis for a Phobos resource retrieval scenario [5]. Basically an operational scenario is assumed in which propellants (or other volatile materials, e.g. methane, ammonia) are produced from Phobos materials and transported to LLO for use on the Moon. This Phobos scenario is compared to the scenario in which similar materials originate on the Earth.

We assume that OTV-like (now called space transfer vehicles or STVs) vehicles are used throughout the scenarios. Lunar OTVs are refurbished at the LEO Station and refueled at LLO with lunar oxygen. Phobos tankers are refurbished at LLO and refueled only at Phobos. The lunar landers are refueled on the Moon with hydrogen either from Earth or Phobos depending on which scenario is being considered [5].

Figure 7 shows the cost benefits (as a function of Earth launch cost) associated with a Phobos scenario as opposed to delivering volatiles to the Moon from Earth. We assume that 225 mT of payload is delivered each flight to the Moon. For an Earth launch cost of $750/lb, possibly characteristic of post-2000 time frames, we calculate a saving of $800 M per flight from Phobos vs the Earth scenario. If we assume (the equivalent of) two flights per year, in one decade, the Phobos scenario would save an amount roughly equivalent to the total cost of the first piloted mission to Phobos.

4. CONCLUSIONS

We are continuing our performance and economic analysis of scenarios involving space resource utilization. Of particular interest are the possible uses and benefits of propellants and volatiles from the Martian moons in the Earth–Moon system (including LEO and on the lunar surface). We also hope to illuminate the role of lunar oxygen and alternative propellant combinations in the development of a 21st century space economy.

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