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Abstract

Several SEI strategies and scenarios are described which emphasize program viability, crew safety, efficient transportation systems, the use of space resources, and the human settlement of Mars. Furthermore, although they are designed to have low launch and program costs, and to be consistent with the President's vision of SEI, they are still able to feature *early* returns to the Moon and early manned expeditions to Mars. These SEI architectures possess this attractive set of attributes because they utilize a split mission scenario - in which the cargo and return propellants arrive at Mars before the crew departs from Earth - and because they emphasize the use of extraterrestrial resources, particularly water. Since water is typically easy to locate, process, and split into propellants, its presence on the lunar surface or the moons of Mars (Phobos and Deimos) can provide extraordinary leverage by reducing the large amount of propellants which otherwise must be launched from Earth. Using an advanced propulsion system (e.g. electric propulsion) for the cargo vehicle and chemical propulsion for the crew module, creates maximum mission efficiency while retaining a reasonable safety margin for the crew. The first human return to the Moon occurs prior to 2000, and is followed shortly by the first human landing on Mars in 2005.

Introduction

There are many ways to go to the Moon and Mars[1]. Only by having clearly defined program goals, philosophies, criteria, and constraints can an intelligent choice be made concerning the best pathways into the cosmos. For example, program constraints are of several kinds, including the physical characteristics and locations of target bodies within the solar system, the projected availability of technologies and human capabilities, and political and economic factors. This last type of constraint is particularly difficult to accomodate because of its inherent subjectivity, but it can be of quintessential importance to program success and viability.

In this paper several potential SEI scenarios and architectures are sketched that are currently under evaluation by General Dynamics. A variety of program characteristics including mission performance, technology status, and costs are presently being studied. This paper specifies and describes the objectives, philosophies, and strategies that have attracted us into this intriguing sector of multidimensional SEI program parameter space.

Fundamental SEI Program Objectives

An outline of the fundamental objectives of the United States' Space Exploration Initiative (SEI) was revealed during President Bush's SEI address on July 20, 1989. However, within his intentionally brief sketch of Lunar/Mars exploration goals, lurks an enormous number and variety of program options. The choice of any coherent option set essentially drives the character of the resulting SEI program.

In this paper five fundamental SEI program objectives are adopted: 1) significant human exploration and scientific investigation of the Moon and Mars system, 2) the eventual human settlement of Mars, 3) the Moon will serve as a technology development site for planetary surface systems, 4) the option is retained to exploit lunar and/or Mars system resources if they are strategically or commercially profitable, and 5) the option is retained for human exploration of the outer solar system (e.g. main belt asteroids).

All five objectives are consistent with the President's statement and each program goal drives many specific aspects of SEI. For example, although permanent human settlement of Mars is one of our clearly delineated goals, the surface of Mars is not our only focus; i.e. a Mars orbital infrastructure will be required to support human missions to the asteroids and beyond. Likewise, prime targets for resource utilization are the moons of Mars (Phobos/Deimos). If they can be economically exploited, Phobos and Deimos may be the initial focal point of the Mars vicinity (but not

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Mars surface) infrastructure - possibly linking directly with the Earth-Moon system.

The goal of Mars settlement immediately compels us to early consideration of Mars in situ resource utilization, because although substantial Mars resource use is not a sufficient condition for settlement, it is a nessary condition. It is also clear that appropriate use of Mars system resources (e.g. for propellants) can provide immense leverage by improving mission efficiency and lowering Earth launch costs. We initially focus on lunar resources in these scenarios because of the Moon's proximity and its potential to contribute propellants for lunar and Mars vehicles. Naturally the technological lessons learned on the Moon will be applied, where appropriate, to the Mars system.

Key SEI Issues

Figure 1 lists several of the key issues associated with SEI. The remainder of this paper is a brief analysis of these issues particularly with regard to their impact on strategies and architectures for SEI.

Program Viability

Program Management and Organization

Crew Safety

Roles of Moon and Mars in total program

Independence from Earth (space/planetary ops)

Space resource strategy

Mission and propulsion options

Human infrastructure strategies

Program flexibility

Figure 1. Key Issues

Topping the list, for obvious reasons, is program viability. The crucial question centers around how the program and its architecture should be structured to facilitate its continued popularity with important decisionmakers. Closely related to program viability is crew safety. Any SEI architecture must be able to guarantee, to a reasonable confidence level, the safety, functionality, and long-term health of its crews during and after the missions. Because of the high public interest and symbolic nature of the space program, SEI will not be long-lived if its astronauts do not "live long and prosper".

Perhaps the most challenging task associated with SEI is the program's management and organization structure. Steinbronn and Cordell (1990)[2] have recently proposed a mechanism for control, definition and development of SEI by an *international* agency. Although it is unlikely that any SEI program initiated during the 1990s will be under international *control*, it is easy to envision SEIs that begin as international cooperative arrangements similar to the Space Station Freedom program, and then evolve in a direction such that power is increasingly diffused. Soviet involvement is also potentially an attractive possibility.

Impressive cases for science and human exploration of the Moon have be made[3] and are a key aspect of SEI as envisioned in this paper. However, in the near term (i.e. prior to 2000) the scale of lunar endeavors will probably be determined by whether or not significant quantities of water are detected in the lunar polar regions as has been previously suggested[4]. A dry Moon would trigger the Mars system water exploration program. Since in the near term, water is the easiest substance to detect, extract, and process into propellants, it is the focus of our initial resource exploration/utilization efforts.

As astronauts venture further into the solar system, their ability to return to Earth rapidly is dangerously decreased. Thus the ability to operate independently of Earth in deep space and on planetary surfaces is crucial. Allied with this requirement is our strategy for space resource use. Essentially, in our search for water, we start with the Moon and (if desired) progress to Phobos/Deimos, and then eventually obtain Mars surface and/or atmospheric waters. Cordell and Steinbronn (1988)[5] have highlighted the important roles that lunar and/or Phobos/Deimos waters could play in any space resource utilization strategy. Bell et al. (1990)[6] have also recently embraced the concept of utilizing (hypothesized) lunar waters as the first extraterrestrial propellant source. The water processors in the Mars system (i.e. Phobos/Deimos and/or surface) are delivered robotically and will have produced appreciable product prior to the arrival of humans.

Our Mars mission philosophy is based upon the belief that appropriately formulated split missions are *safer* than conventional mission modes. We enhance the mission performance by utilizing an advanced propulsion system with the cargo vehicles and maximize crew security by adopting chemical propulsion and sprint-style mission profiles for the crew vehicles. The goal is to lower Earth-to-orbit propellant launch requirements without taking any unnecessary risks with the crew. Several options are described below.

Upon arrival at Mars our strategy for human infrastructure emplacement becomes paramount. The basic question involves whether to concentrate the infrastructure buildup initially in orbit, on the surface, or to accomplish both simultaneously. This question is influenced by our ability to produced propellants at Phobos/Deimos, our initial science and exploration goals, and several other factors.

Finally, it is important to remember that many important questions relevant to the availability of future advanced technologies (e.g. nuclear propulsion), space resources, program management, and several other areas will not be answered until sometime in the future. Therefore, we must retain flexibility in virtually all aspects of our SEI plans (e.g. goals, strategies, and mission and vehicle concepts) so that promising future developments may be included in SEI programs without creating major dislocations in the program structure.

SEI Program Viability

Program viability is a concept riddled with intangibles, subjective judgments, and extremely complex political situations with the potential to positively influence national and global affairs at the highest levels.

Figure 2 lists several points that relate closely to SEI architecture and strategy considerations. Although robotic systems will continue to play a pivotal roles in SEI, it must be clear to all observers that SEI is essentially a *human* exploration program. Likewise, although the Moon will be our first goal for robotic and human exploration, the lure of Mars is such that potential SEI supporters must perceive that Mars is an ultimate goal. Further, those initial human forays to Mars must not occur too far in the dim future (e.g. beyond 2010).

It is likely that when program costs are placed into perspective, very few critics will judge them to be excessive. Regardless of the price tag, however, the returns from SEI - in all forms - must be intriguing and titillating. Finally, SEI is naturally a *global* program and has the potential for increasing favorable interactions and cooperation among many nations of the world. A more complete discussion of SEI rationales is contained in Cordell (1990)[7].

- **Must focus on Human exploration and settlement**
  - "We dont' give tickertape parades to robots!"
  - Important to real-time science/engineering
- **Mars should be a relatively near-term (pre-2010) goal**
  - High public interest
  - Interesting science (environmentally relevant)
  - Most Earth-like extraterrestrial site
- **Investment must be viewed as providing acceptable returns**
  - Frequent, visible program milestones
  - National Prestige
  - Technology development
  - Economic competitiveness
  - Human adventure and spirit
  - Education and motivation
  - New commercial prospects
- **Program must be seen as consistent with and contributing to a "New World Order"**
  - Significant international involvement
  - Gradual diffusion of power
  - "U.S. Leadership" must be reinterpreted

Figure 2. Program viability factors.

Crew Safety Philosophy

Healthy, optimally functional crews are essential objectives of any SEI architecture. Perhaps the most straightforward way to increase the probability of this is to shorten mission times. Initially, Mars total mission times may have to be relatively limited because of psychological and social factors which will be difficult to simulate and assess prior to launch. However, eventually, when a Martian infrastructure becomes established and as crew hazards become better characterized and understood, our goal is to minimize interplanetary transit times and (within reason) maximize crew time at Mars.

Second, a near-term SEI must present the crew with every possible option for survival in the event of a major failure during the mission. Even if never utilized, the availability of such contingency measures will provide psychological advantages to the crew.

In a split mission scenario, the main operational crew hazard involves the requirement for rendezvous with the cargo ship after the piloted vehicle has captured into Mars orbit. It is suggested here that two emergency crew return modes (i.e. abort modes) be available: 1) a flyby capability (available with sprint missions), and 2) a powered Mars escape, Earth return capability. The second option would require that sufficient propellants be carried onboard to return the piloted vehicle. While this will somewhat degrade mission performance, it is expected that Option #2 would only be required on the very earliest manned missions.

Third, ideally crew members arriving at Mars (or elsewhere) for the first time should be greeted with secure caches of propellants, consumables, and mission hardware to enable them to be more concerned with mission-related goals and less preoccupied with their own survival. Autonomous water processing systems delivered during robotic precursor missions can provide a "Club Mars" atmosphere! This would be particularly welcome to initial crews who have experienced isolation and confinement unprecedented in human history and then must confront the frozen sands of Mars.

Fourth, to ensure crew safety and security, it is suggested here that the piloted vehicles initially have minimal dependence on new, uncertain, and/or high risk technologies. In the near-term, this would obviate the use of advanced propulsion in the crew vehicle. After a few successful cargo missions, the "advanced" systems would become "man-rated" and then be used for transportation systems with humans also.

Finally, we insist here on space and planetary surface operations that are safe as well as efficient and productive. This is a key consideration in the adoption of a human infrastructure strategy and exploration operations for the Mars system.

Split Missions - A Key Near-Term Feature of SEI

Split mission scenarios are central to the SEI strategies and mission concepts proposed in this paper. Figure 3 shows some of the advantages and potential drawbacks of a split strategy.

Previous studies (e.g. Ref. 8) have established that separating the delivery of cargo and crew to Mars typically results in significant performance advantages. But the basic motivation behind our emphasis on them is their ability (by safely caching propellants and other key materials on Mars) to make the Martian environment seem more accomodating to first-time explorers. It also allows us to use advanced and conventional propulsion systems on the cargo and crew vehicles respectively. A byproduct of this strategy is that detailed science investigations can begin prior to crew arrival and be poised for immediate human supervision.

PROS

- Performance is typically better
- Cargo (e.g. return propellants, consumables) safely delivered/stored at Mars before crew departure from Earth
- Science operations begun robotically
- Mars resource utilization initiated prior to crew arrival
- Allows different propulsion systems for piloted and cargo vehicles

CONS

- Increased Mars orbit operations complexity (e.g. piloted vehicle must rendezvous with cargo vehicle at Mars)
- Cargo/Resource Processor status monitors must be highly reliable

Figure 3. Split Missions: Pros & Cons.

A disadvantage of split missions is the necessity for the piloted vehicle to rendezvous with the cargo vehicle in Mars orbit, and to generally increase the complexity of orbital operations near Mars. Our current assessment of this problem[9] is that the split mission's only signifcant risks are mitigated acceptably by the previously mentioned crew emergency return provisions.

Initial Infrastructure Strategy At Mars

Figure 4 shows an assessment of the important alternatives and issues involved in formulating any human infrastructure strategy at Mars. Analysis here is dominated by several unknowns, including the feasibility and ease of propellant production on Phobos/Deimos vs. Mars surface. Several factors - accessibility, carbonaceous compositon, simple landing requirements - appear to favor Phobos/Deimos as the first beachhead near Mars. However, the moons' milli-g, dusty environment may introduce significant hazards and difficulties into water extraction operations. Instead, we may opt to proceed directly to the Martian surface to access the water use potential in the atmosphere and surface materials. As the Mars infrastructure expands, it is anticipated that operations on the Mars surface will become safer than remaining in orbit.

Alternatives Include:

1) Orbital emphasis,
2) Surface emphasis,
or 3) Simultaneous growth

KEY ISSUES

- Feasibility of propellant production on Phobos/Deimos
- Relative ease of propellant production on Phobos/Deimos vs. Mars surface (using atmospheric or surface resources)
- Safest location for Mars crew (Orbit, Surface, Phobos/Deimos?)
  - Orbital hazards (meteors, radiation, etc.)
  - MEV risks
  - Space resource use strategy
  - Effects of infrastructure evolution
- Moon/Mars exploration strategy contrasts: Key Factors
  - Exobiology
  - Atmosphere
  - Surface conditions (gravity; T, P, & diurnal/seasonal cycles)
  - Ascent/Descent delta-V
  - Presence of water (and other useful substances)
  - Surface area and terrain types
  - Travel times and crew return modes

Figure 4. Mars Infrastructure strategy .

Infrastructure strategy is expected to differ significantly between the Moon and Mars. Since Mars is a much more complex, more Earth-like body than Mars, we may decide to delay large-scale human operations on the Martian *surface* until we have probed it further with robotic devices, possibly directed by humans in Mars orbit or at Phobos or Deimos.

Space Propulsion Options

Our approach to decisions about specific propulsion systems is to maintain sufficient flexibility so that whichever advanced system becomes available shortly after the year 2000, it will be easily accommodated within the program. The basic space propulsion options are shown in Figure 5.

Early Split Mission Propulsion Philosophy:

1) Cargo vehicles use most efficient system available,
2) Piloted vehicles use chemical systems

Option I: Assume low power (100 kw) SEPS is available (Flight tested in 1970s)
Cargo: SEPS (all return props, consumables, HW)
Crew: Chemical (with Earth aerobrake option);
Possible sprint mission;
Abort modes: 1) flyby, 2) capability for Mars escape and Earth return without cargo vehicle rendezvous

Option II: Assume multimegawatt NEP is available
Cargo: NEP (all return props, consumables, HW)
Crew: Chemical (with aerobrake option)
Possible sprint mission;
Abort modes: Same as above

Option III: Assume NERVA Derivative is available
Cargo: NERVA (all return props, consumables, HW)
Crew: Chemical (with Earth aerobrake option);
Possible sprint mission;
Abort modes: Same as above

Evolutionary Philosophy:

As advanced systems become more reliable (e.g. after a few cargo missions, they become "man-rated" and are used in piloted vehicles.

Figure 5. Propulsion and Mission Modes.

For early missions to Mars, cargo vehicles will use the most efficient propulsion system available. This may be nuclear electric propulsion (NEP), a NERVA derivative, a low-power electric system like solar electric (SEPS) which was flight tested during the 1970s, or even some combination of these. For the earliest missions the crew will be transported to Mars by chemical propulsion, because of our extensive experience with it and its high reliability. The crew vehicle weight will be relatively low and thus very fast (sprint) trajectories should not be particularly expensive. Another option is to use cycling orbits such as those proposed by Aldrin (1990)[10] for routine, safe transfer of crews between the Earth and Mars.

If water is located on the Moon, the chemical vehicles will be fueled and launched from the lunar vicinity. In the case of a dry Moon, Phobos/Deimos could contribute most of the chemical propellants.

Eventually the piloted vehicles will also be driven by advanced propulsion. As advanced systems become increasingly reliable (e.g. after a few cargo missions), they become "man-rated" and are used for piloted vehicles. After this transition, lunar propellants would be utilized by lunar excursion vehicles and Earth-Moon traffic.

A Near-Term SEI Strategy Featuring the Search For Water

Figure 6 shows an overall strategy for SEI with a possible schedule and the key decision points.

Sometime during the mid-1990s we will send robots or humans (or both) to the lunar polar regions to search for Water. Bell et al. (1990)[6] suggests the first human return to the Moon should be in 1995. If this schedule should prove unrealistic, a robotic orbital and/or surface mission

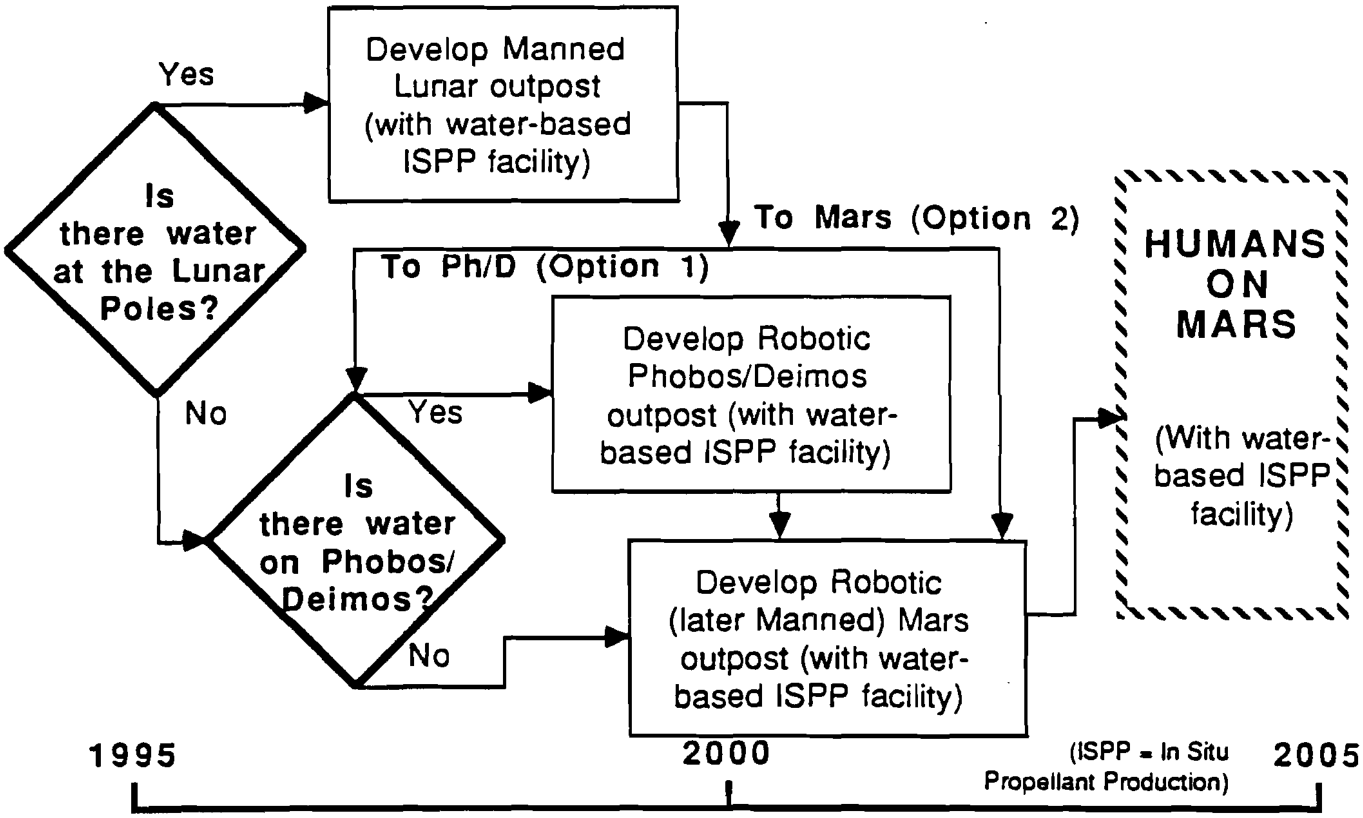

Figure 6. An SEI strategy and schedule with a focus on water exploration.

to the Moon could be launched in 1995 with humans to follow sometime later (before 2000). Finding abundant lunar waters is a low probability enterprise, but if it should succeed, the lunar polar outpost will be developed along with a water processor/in situ propellant production (ISPP) plant. Astronomical and geological science will also be pursued on the Moon.

Sometime in the late 1990s we will send a robotic mission to Phobos/Deimos to determine its water status. If it is ascertained that we desire and are capable of developing Phobos/Deimos resources, an outpost - initially robotic, later man-tended - will be established on the moons with an ISPP capability. This step would occur either shortly after we get a negative result for the Moon or after lunar water resources have been developed and Mars is becoming our focus.

There is little doubt that water resources can be utilized on Mars itself. The atmosphere is often water saturated (at night) and the total water reservoir currently on Mars is estimated as comparable or exceeding Earth's. If a robotic system is delivered to the Mars surface a few years prior to the arrival of humans, it should be possible to have produced significant amounts of propellants and other consumables and have stored them at the planned human landing site.

EXOFUEL: An Example of a Possible Commercial Strategy Involving the Martian Moons

Cordell (1985)[11] suggested that volatiles (e.g. water) on Phobos/Deimos might be efficiently retrieved for profitable use in the Earth-

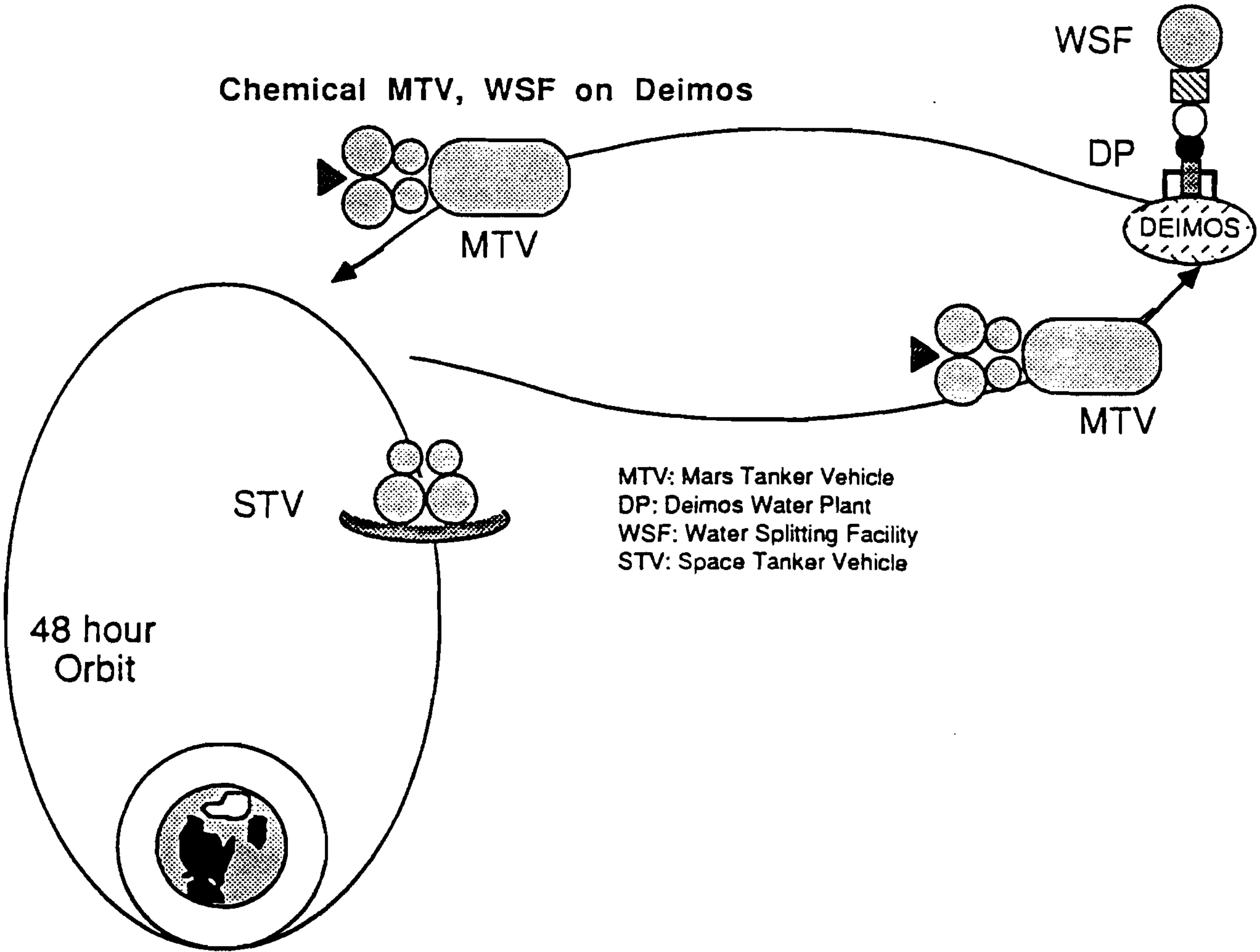

Figure 7. EXOFUEL Scenario Overview.

Evaluation Criteria*	Scenarios				
MTV Propulsion	Nuclear Steam Rocket (NSR)		Chemical		Nuclear Therm (NTR)
WSF Location	LEO	MTV	Deimos	MTV	MTV
Net Props to LEO (mT)**	443	430	1224	1198	1883 (O only)
Net Props to LEO/ Total Wt to LEO**	0.72	0.91	2.78	2.72	3.04
Net Props to LEO/ Total Water Production**	0.18	0.17	0.49	0.48	0.75 (H from Earth)
Infrastructure Emplacement Cost ($B)	14.5	11.4	11.7	11.8	13.6
Savings/Profits Per Mission ($M)	631	610	1920	1877	2800
Number of Missions to Break Even	23.0	18.7	6.1	6.3	5.0
Technology Risk	Mod	Low	Low	Low	Mod
System Risk	Low	Mod	Low	Very Low	Mod-High
Political Risk	Mod	Mod	Very Low	Low	Mod

*** Assumes 2500 mT of water produced at Deimos per mission**
**** Values are on a per mission basis**

Figure 8. EXOFUEL Scenario Evaluations Overview

Moon system. More recently this work has been supported by the General Dynamics Corporation and has revealed that resource development on the Martian moons has the potential to stimulate the development of a Mars economy as well as possibly provide an economic rationale for the human exploration of Mars.

Figure 7 shows one scenario investigated in our analysis[12]. A water extractor and ISPP plant (i.e. the water splitting facility and Deimos plant) on Deimos produces propellants that are retrieved to a high elliptical Earth orbit. From this orbit the Martian propellants are transferred via an STV to LEO where they are used to fuel lunar or planetary spacecraft.

Several scenarios of this type were investigated. Figure 8 summarizes our performance and cost data generated during our initial analysis of the potential of the martian moons for commercial development. Note that chemical vehicles can deliver well over 1000 tons of propellants to LEO per mission which saves almost $ 2B over similar propellants launched from Earth. Typical total infrastructure emplacement costs are between $ 10-12 B. NERVA derivative vehicles have even superior performance but are not required for the scenario to be profitable. This seems to be the type of endeavor that could be initially supported by government funds but could eventually be commercialized by the private sector.

We view EXOFUEL to be illustrative of merely one interesting example of the impressive potential of space resources to stimulate humankind's aggressive, efficient, and safe exploration of the solar system.

Our quantitative analyses of SEI architectures that are associated with strategies and scenarios of the types described in this paper are continuing.

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