Extending Human Presence into the Solar System

An Independent Study for The Planetary Society on Strategy for the Proposed U.S. Space Exploration Policy

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Executive Summary

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We propose here a staged approach to human exploration beyond low Earth orbit (LEO). We believe such a plan must be adopted if the overall funding profile is to be kept within the bounds that are likely to be acceptable to the many future Congresses and Administrations that must “sign on” to the Exploration Initiative if it is to succeed.

Stage 1 features the development of a new crew exploration vehicle (CEV), the completion of the International Space Station (ISS), and an early retirement of the Shuttle Orbiter. Orbiter retirement would be made as soon as the ISS U.S. Core is completed (perhaps only 6 or 7 flights) and the smallest number of additional flights necessary to satisfy our international partners’ ISS requirements. Money saved by early Orbiter retirement would be used to accelerate the CEV development schedule to minimize or eliminate any hiatus in U.S. capability to reach and return from LEO.

Stage 2 requires the development of additional assets, including an uprated CEV capable of extended missions of many months in interplanetary space. Habitation, laboratory, consumables, and propulsion modules, to enable human flight to the vicinities of the Moon and Mars, the Lagrange points, and certain near-Earth asteroids. Development of human-rated planetary landers is completed in Stage 3, allowing human missions to the surface of the Moon and Mars beginning around 2020. The overall plan is summarized in Table 1.

A key to this vision is the requirement to complete assembly of the ISS and to retire the Shuttle Orbiter, without in the process incurring another lengthy hiatus in the ability of the United States to conduct crewed spaceflight operations. To this end, we recommend phased development of the new CEV, with the “Block 1” version designed for LEO access and return only, with a later “Block 2” version suited to the requirements of interplanetary missions. The CEV would be launched on a new human-rated vehicle, possibly based on the existing Shuttle solid rocket motor (SRM), augmented with a new liquid upper stage. Such a system could be available before 2010. With Orbiter retired after U.S. Core complete and with international agreement to proceed, any remaining assembly tasks can be completed by the heavy-lift launch vehicle (HLLV) that must be developed to support later stages of the Exploration Initiative, by use of expendable launch vehicles (EELVs) as appropriate, or on suitable international vehicles such as Ariane or Proton.

Stages 2 and 3 of the proposed Exploration architecture will require heavy-lift launch capability well in excess of the 20–25 metric ton capacity of the present evolved EELV fleet. We believe these requirements can best be met, at least initially, by means of designs that utilize existing Space Shuttle components (e.g., the SRM and External Tank). Some proposed Shuttle-derived HLLVs have a payload capacity in excess of 100 metric tons and offer a near-term approach to meeting Exploration requirements with a minimum of non-recurring investment.

Prompt studies to confirm our recommendations are needed in areas of early CEV design for Block 1 capability to and from LEO, to establish the minimum number of Shuttle flights necessary to meet international requirements, to find the best launch vehicle for the CEV, and to perform trade studies for HLLV needs and configuration.

Overview of Exploration Plan

Stage One, access to LEO, through 2010
• Shuttle-Orbiter return to flight (RTF), complete the ISS through at least "US Core Complete"
• Select and demonstrate launch vehicle for CEV
• Demonstrate early CEV use for crew transfer at the ISS
• Negotiate with international partners to obtain best way to transport remaining heavy modules to the ISS
• Retire Orbiter as soon as above steps are completed
• Costs distributed across full Exploration window
Stage Two, interplanetary cruise, through 2015 and beyond
• Develop interplanetary cruise capability; uprated CEV, and necessary additional modules for the destination selected
• Ensure HLLV available, probably a Shuttle-derived HLLV
• Enable lunar orbit missions, remote sensing, Rovers with sample return
• Enable visits to Sun-Earth-Lagrange #2, astronomy, etc.
• Enable visit and study of near-earth objects (NEOs)
• Enable visits to Mars vicinity, including moons Phobos and Deimos. Include remote sensors and Rover with return samples. Begin infrastructure placement. Select sites.
• Select destinations as appropriate: science, public, other interests
Stage Three, human surface landings, 2020 and beyond
• Prepare infrastructure for moon and/or Mars bases
• Build on thorough preparation in preceding stages
• Initiate human landings at selected destinations
• Plan for future solar system exploration

Introduction

The recent Presidential Directive to focus NASA's future on exploration via "the Moon and on to Mars" has invigorated the space community and many of the general public. Meeting these goals while remaining within realistic funding expectations is foreseen as the major difficulty in meeting this challenge. The Planetary Society has commissioned this Report to encourage support for this new venture and to suggest a workable strategy for human exploration of the solar system, with the specific goal of placing humans on the Martian surface at the earliest possible moment, while allowing costs to be managed at reasonable levels.

It will be suggested below that the exploration can be conducted in three stages. Stage 1 is the early development of a new Crew Exploration Vehicle (CEV), as the President has directed, accompanied by the development of a launch vehicle to transport the CEV to and from low Earth orbit (LEO). Success with the CEV will lead to missions beyond LEO. We are recommending that strong consideration be given to a specific design using the Shuttle solid rocket motor (SRM), together with a new liquid propellant upper stage, for this role. We believe that this evolutionary development will be the quickest and least expensive path to realizing a U.S. capability to send humans to LEO, and beyond, without the use of the Shuttle Orbiter. This capability should be available well before 2010, the date by which the Orbiter is to be retired. By this time, the International Space Station (ISS) should have reached at least the "U.S. Core Complete" stage, and NASA should have reached an agreement with our international partners about how best to complete our obligations to them.

The CEV should be designed explicitly to have sufficient on-orbit life that it can be resident at the ISS for extended periods, thus providing the emergency crew return capability that, at present, is available only via the Russian Soyuz spacecraft. The long-duration requirement is an obvious necessity in an exploration vehicle. In addition, the crew-return vehicle (CRV) function requires that it be capable of remaining stable and quiescent, with minimal power drain, for long periods.

We believe that there are significant advantages, both for the United States and for the ISS partners, associated with developing the new LEO transportation capability as early as possible. All partners would benefit from an earlier beginning of the benefits of having larger multinational crews on the ISS. The remaining heavy modules for the ISS might be better transported to the ISS by means of a Shuttle-derived HLLV, to be discussed below. It should again be emphasized that the proposed early development of a new LEO transport system is intended to achieve earlier and more frequent access to the ISS for all partners. The Orbiter would then be retired promptly to save the high costs of maintaining Orbiter operations, with the cost savings making funds available for Stages 2 and 3. The ISS can be used not only by our international partners but also by U.S. crews for tasks associated with solar system exploration, including qualifying personnel for long-duration missions and for studying social-psychological interaction within larger crews. Remaining cargo can be delivered to the ISS by other vehicles, including non-U.S. launchers.

A key Space Shuttle capability that cannot be provided in a CEV designed for voyages beyond LEO, or by the Russian Soyuz or Progress systems, is the so-called downcargo capacity of the Shuttle. The Shuttle's large cargo bay enables the return from the ISS of rack-sized experiments, samples, and equipment needing to be analyzed, refurbished, or upgraded on the ground. (Shuttle downcargo typically also includes crew laundry, other recyclable items, and various waste and trash, but such use is largely opportunistic rather than reflective of a fundamental need.) However, these items, while valuable, need not be returned in a vehicle designed to meet human-rating safety standards. It should be possible, indeed relatively easy, to design an automated semiballistic vehicle, possibly expendable, for the purpose of ferrying standard ISS rack-sized cargo up to the ISS and returning other items safely to Earth. The basic technology was first proven in the Corona program, during which literally hundreds of film-carrying capsules were returned to Earth from reconnaissance satellites. It may be noted further that the recently cancelled Alternate Access to Space program could also accommodate substantial downmass capability.

Stage 2 initiates human exploration of the solar system, with a variety of destinations including "near Earth objects" (NEOs) such as asteroids; certain unique gravitational locations such as the Sun-Earth Lagrange points, which are of special interest to astronomers; and the vicinities of the Moon and Mars. The lunar and Mars reconnaissance missions would be analogous to the Apollo 8 and 10 missions to the Moon more than 30 years ago, but they would involve extensive robotic and remote sensing activity, controlled either from a manned laboratory module or from the Earth, whichever is found to be most appropriate. The eventual sequence of visits can be decided later, depending on the public interest in and scientific importance of each step.

Stage 2 requires the development of an interplanetary cruise vehicle configuration that must include at least an extended-duration CEV or an appropriate derivative vehicle, in addition to a modest laboratory for surface robot control, returned sample analysis, and physiological experiments. A habitation module also is required. These might be derivatives of the current ISS laboratory and habitation module designs. Such commonality is, however, limited by the fact that considerable differences will exist between the requirements for use on the ISS and those for interplanetary missions, including the need for additional radiation shielding, upgraded avionics, and longer-duration life support. Consumables carriers for propellant and other crew expendables also will be required. Human-robotic synergism is expected to play an essential role in the scientific, engineering, and new technology aspects of emerging human exploration of the solar system. As such, it is expected to become an important component of our Stage 2 program. Finally, there will be a clear need for a heavy-lift vehicle to transport these large items to the selected staging point, whether in LEO (as is likely for early missions) or at a Lagrange point (which may be advantageous in the longer term).

We believe that the most suitable and least expensive heavy-lift option, at least in the near term, will be an unmanned Shuttle-derived heavy-lift launch vehicle (HLLV). Numerous design configurations for such vehicles have been proposed, offering payload capability in the range of many tens to more than one hundred metric tons [1]. Competing options include the use of heavy-lift versions of the Atlas V or Delta IV vehicles, having payload capacity in the 20-25 metric ton range, and a variety of new, “clean sheet of paper” designs. Although we have made a specific recommendation, the relative merits of the various options should be confirmed in trade studies, with due attention to the fact that for some options, mission-enabling hardware of proven reliability already exists. Depending on the retirement date finally chosen for the Shuttle Orbiter, the first use of the HLLV could well be in connection with completion of the ISS.

Implementation of Stage 2 should permit visits to any of the destinations above by 2015. Note that human landings on the Moon or Mars are not included in Stage 2, although landings on the Martian moons (Phobos or Deimos) could be made, as they have negligible gravitational attraction and no atmosphere. This arguably will be both safer and more cost-effective, early on, than going directly to the planetary surfaces, as human landing and ascent vehicles would not be required.

In Stage 3, the development of human landers for the Moon and Mars is completed. It is conceptually attractive to envision using the same basic lander design for both planets and, indeed, such commonality should be pursued where possible. However, there are several basic differences in the requirements that must be imposed upon the two systems, and for which the final design must account. The lunar lander requires a descent Δv of approximately 1.85 km/s from low lunar orbit; in the absence of an atmosphere, the ascent requirement to the same orbit will be similar, for a total Δv of approximately 3.7 km/s. A Mars lander must employ an aeroshell for the entry phase, and the descent propulsive Δv will be considerably less than for a lunar landing, while the ascent Δv alone will be of the order of 4 km/s. Further design differences will arise if *in situ* Martian resources are used to provide fuel for the ascent phase. It is likely that a lander designed for Mars will be an “over-design” for use at the Moon. However, the ascent stage of a Mars lander might, by itself, serve as a single-stage, fully reusable lunar lander. It may also be desirable to flight test the Mars vehicle at the Moon.

The interplanetary cruise configuration needed in Stage 3 is largely identical to that used in Stage 2, with the addition of the lander. It is believed that by phasing the new designs across three stages of activity, costs can be more uniformly distributed across the fifteen-year development period. We believe that human landings on the Moon or on Mars can begin about 2020.

Approach to Human Space Flight Program Design

Destinations for the Space Exploration Enterprise

We believe that it is the destiny of humankind to explore deep space personally. It is not a question of "if" but rather one of "when," "where," and "how." The debate as to whether robotic spacecraft alone can adequately and more effectively explore space for scientific purposes will continue, but it is essentially beside the point. Whether humans should travel and explore is very much a societal rather than a scientific question and, historically, whenever the question has been asked, a significant fraction of humankind has answered "yes." Prior generations have thrived by exploring beyond their known boundaries; we are all the descendants of successful past explorers. So it will be with the reach of humanity into deep space.

"When" is now. We have made shamefully little progress in exploration beyond LEO in the decades since Apollo. Thirty-five years ago, men walked on the Moon and returned safely to Earth. After a few missions, that marvelous capability was abandoned, and it no longer exists.

Apollo was very much an instrument of the Cold War, a peaceful solution to the problem of how the United States could compete successfully with the Soviet Union for influence in the world. Apollo was thus enabled by particular world circumstances that no longer exist. No other problem of similar scope facing America today is perceived to require a new space enterprise for its solution, and an Apollo-like effort is therefore deemed irrelevant and unaffordable in terms of solving a known problem.

The United States, however, surely will continue to support a program of manned spaceflight. To abandon the capability to put humans in space, when other nations can, would be to consign America to the second rank of nations, a clearly unacceptable position. What is needed today is a steadily progressive, regular, and affordable program to enable the "where" and "how" to which we have referred. Significant new goals and destinations must be reached on a regular basis, but the political support necessary to sustain a "crash" program like Apollo cannot expected.

The ultimate "where" for the 21st century is Mars. The human destiny is clearly to explore our most Earth-like neighbor planet, and perhaps one day to colonize it. But a huge program with Mars as the immediate and only target is neither technically wise nor politically sustainable at present. A stepped strategy similar to that developed by the International Academy of Astronautics, "The Next Steps in Exploring Deep Space" [2], provides a very attractive foundation for the "how" of initiating a program of human space exploration today.

What is needed to sustain funding and public support for human activities in deep space is an exploration strategy with a series of intermediate destinations that are publicly exciting and scientifically rewarding, and that incrementally build the capability to send humans to Mars. In this report, we provide one possible approach to the design of just such a program.

Two particular destinations in near-Earth space could serve as useful and interesting first steps toward exploring deep space. The closest is the Moon, which many consider to be the best first destination for a human space exploration enterprise eventually leading to Mars. Numerous *in situ* scientific investigations remain to be performed on the

Moon in order to add to our understanding of the origin and evolution of the Earth, and many have argued that these investigations warrant the presence of human intelligence. Although the Moon lacks an atmosphere and has only half the surface gravitational acceleration of Mars, it may nonetheless offer numerous advantages as a "testing ground" for human missions to Mars, lessening the steepness of the learning curve for future Mars expeditions.

Scientific interest in returning to the Moon remains high, and the Moon has potential utility as a stepping-stone for the exploration of Mars. In addition, there will be great interest in the Moon among spacefaring nations that have not yet sent humans there—both for national prestige and as a confidence-building step before participating in an international Mars expedition. Europe presently has a lunar robotic mission, and Japan, China, and India are all developing their own such missions. The Moon remains a valid destination in its own right, and any transportation architecture should be designed with this in mind.

A second useful destination in near-Earth space is approximately four times as far away as the Moon, near the very edge of Earth's gravitational field—the Sun-Earth Lagrange Point 2 (SEL2), located 1.5 million kilometers from Earth in the anti-solar direction. The Lagrange points are five locations in space where an object can reside in equilibrium between the gravitational attractions of the Sun and Earth and the centripetal acceleration due to its revolution around the Sun. Small, periodic stationkeeping maneuvers (a few meters per second per year, minuscule by deep space standards) are required to remain at any of the Lagrange points.

SEL2 is an excellent location for the large space telescopes of the future because it has an unobstructed view of the universe without interference from planets such as Earth or the Moon, offers a benign thermal environment without dust, provides a weightless environment for large mirrors, and encompasses a vast expanse for distributed apertures. Travel to SEL2 is energetically easier than landing on, or even orbiting, the Moon. Although mathematically SEL2 is a "point" in space, for practical purposes it is a region large enough to accommodate countless human and robotic spacecraft.

Future space telescopes are planned to operate at SEL2, including the successor to the Hubble Space Telescope (HST), the James Webb Space Telescope. There will be a continuing scientific impetus and public interest in advanced telescopes that can search for, study, and image Earth-like planets around nearby stars, as well as searching for evidence of extraterrestrial intelligent life. Any exploration architecture must recognize the public ownership and support of this objective, because ultimately these telescopes will require servicing just as the HST has.

The tremendously successful, scientifically productive HST has taught us an early lesson in the importance of human servicing of these assets once they are in space. Without the human servicing mission to correct the optics of HST, it would have been a disastrous failure. Without subsequent missions to replace ailing subsystems and to upgrade its instrument complement, HST would not have been remotely as productive as it has been. In the International Academy of Astronautics (IAA) architecture, regular servicing of SEL2 assets is one element in the logic of placing the interplanetary staging node at

SEL2; the appropriate mix of human vs. robotic servicing activity is one of many issues remaining to be addressed.

As an aside, we note that the tremendous outcry over NASA's decision to terminate manned Hubble servicing missions following the loss of *Columbia* offers some perspective on the value placed by the public on world-class astronomy. Because even higher-quality astronomy can be enabled from SEL2, we have some confidence in the value, from the public's perspective, of SEL2 as a significant destination for the exploration program.

SEL2 is also an excellent point from which to stage missions beyond Earth's gravitational field. Such a staging node is of no value for a single planetary expedition or for an architecture built primarily around expendable mission hardware. Assuming, however, that an interplanetary vehicle stationed at SEL2 is reused for many trips to multiple destinations, the energy savings achieved through the use of such a staging node are significant. The vehicle need be lifted to this point on the edge of the Earth's gravity field only once, and fuel and supplies can be ferried robotically on slower but more energy-efficient trajectories, possibly using electric propulsion (EP) vehicles. In such an architecture, servicing of this vehicle and other SEL2 assets becomes a routine operation. Astronauts assembling and servicing these assets at SEL2 will be, at the same time, developing the capability to live and work in much the same environment as for the journey to Mars.

Beyond SEL2, the next possible destination short of Mars itself would be one of the near-Earth asteroids. To rendezvous with a near-Earth object (NEO) and return would require substantially less than a year, a somewhat less ambitious goal than a probable three-year round trip mission to Mars. Once astronauts are successfully commuting to SEL2 and working there, the additional capability required to visit an asteroid is essentially the ability to travel in space for several months without logistical support from Earth. A larger vehicle with more onboard life-support resources is needed. However, to "walk" on an asteroid and return samples requires little more than traditional extravehicular activity (EVA) equipment for Earth orbit applications, since the surface gravity of the asteroid will be negligible. NEOs are of great interest for a variety of reasons, including the threat they present to Earth and their potential as a source of raw materials. They are also important scientifically because they are primordial objects, essentially unchanged since the formation of the solar system, and are thus likely to hold clues to the origins of humanity. A near-Earth asteroid mission would have considerable public appeal as an exciting and potentially engaging popular adventure, and it is a potentially ideal intermediate step to reaching Mars. Such missions can be accomplished with a total Δv of as little as 4-5 km/s, less even than for a lunar landing.

Once humans have visited an asteroid, the next step could be to orbit Mars. To reach Mars orbit and return safely will require more support cargo than needed for an asteroid mission. Thus, specialized cargo vehicles must be developed and utilized for this step. Because the cargo can be sent well ahead of the crew, lengthy trip times will not matter, allowing the use of more efficient trajectories and low-thrust propulsion systems that would be unsuited to human missions. This capability is not needed early in the human exploration enterprise and therefore can be developed later and over a longer period of time, thus requiring later and more modest year-to-year funding.

A Mars orbit mission would provide the experience of operations in Mars proximity without the challenge of safely descending to the surface and ascending from it to rendezvous with an Earth return vehicle, exactly the role of the Apollo 8 and 10 lunar orbital missions in their time. From Mars orbit, humans can command robotic vehicles on the surface in real time, a major step toward *in situ* human intelligence operating on the surface of Mars, in contrast with the operational impedance imposed by the 10- to 20-minute round trip speed-of-light delay for current robotic Mars missions. Investigating Mars from Mars orbit in this manner is functionally much closer to having human capability on Mars' surface than it is to the current Earth-based human-operated robotic missions.

To achieve orbit about Mars and to depart for Earth from such an orbit is easier and safer than an excursion to the surface. A more ambitious alternative would be to land and operate on the surface of one of the two Martian moons, Deimos or Phobos. Some minor additional propulsive capability would be required, but it is negligible in comparison to that needed to land on and return from the Martian surface. Also, no atmospheric entry systems are required. Operating from a Martian moon is indeed analogous to Apollo missions operating on our own moon's surface, but without the large propulsive requirement and dangerous ascent required to climb out of our moon's potential well.

Once astronauts have worked successfully in orbit around Mars or on the surface of Deimos or Phobos, they will have acquired the best possible prerequisites for the final step to the Mars surface. The human entry, descent, and landing (EDL) vehicles and the Mars Ascent Vehicles (MAVs) would be developed in parallel to the ongoing human Mars orbit or Mars moon missions. These vehicles could be delivered to Mars' vicinity robotically, well in advance of human missions to the surface. They would be placed at the staging point for human missions to the surface, either in orbit about Mars or on a Martian moon.

If desired, it would be possible to conduct one or more telerobotic test flights of the descent and ascent vehicles before using them to go to the surface and return safely. Most of the surface excursion hardware should be reusable, except (possibly) for heat shields and, if used, parachutes. Thus, the various landing craft should remain at Mars, as they do not need to be returned to Earth. Refueling would be accomplished either from propellant delivered from Earth as cargo or from *in situ* production by pre-emplaced processing plants delivered as cargo.

It is worth noting that once the landing phase has been initiated at either the Moon or Mars, the use of surface facilities and pre-emplaced assets as an "abort" option becomes viable. With the inherent advantages provided by gravity and material for radiation shielding, as well as redundant sources of nuclear power and tools, options for surface survival may in some cases be better than for an escape to Earth.

We have proposed an exploration architecture that places humans in lunar and Mars orbit substantially before surface landings are contemplated. We recognize that there will be disagreement over whether to conduct orbital missions at the Moon or Mars prior to landing, and for that matter whether to return to the Moon prior to initiating an expedition to Mars. In our view, these questions need not be answered at present. When

answers are made, they will depend as much on the background and perspective of those deciding as upon any specific technical criteria. It is our intent here to point out the destinations that have been "enabled" in each Stage of the proposed architecture, deferring for now any consideration as to which will be pursued, and when.

We have outlined a step-by-step plan for progressive human exploration and exploitation of four destinations—the Moon, SEL2, near-Earth asteroids, and Mars itself each of great scientific importance and each requiring only one major new advance in capability beyond the prior destination. Following this plan, we can make steady progress toward placing humans on the surface of Mars, at reasonable costs, while maintaining an exciting human enterprise in space. The proposed destinations are justified by their public interest, scientific merit, and exploration value, and they provide for steady, measurable, and timely progress in a logical manner toward the ultimate goal of Mars exploration. In this sense, the proposed architecture is analogous to the progression from Mercury to Gemini to the early Apollo missions in building toward the final outcome of Moon landing on July 20, 1969.

International Cooperation

The authority to conduct international space activities is granted to NASA under Section 205 of the National Aeronautics and Space Act of 1958. Since its founding, NASA has engaged in thousands of cooperative projects with foreign nations ranging from training and experimentation to the construction of the International Space Station. Further such cooperation throughout the full range of previous activities appears a likely feature of any future Lunar-Mars program and is specifically mandated in the National Space Policy Directive for Moon-to-Mars.

1. Roles

European interest in "'long-term'" robotic and human exploration of solar system bodies" is evidenced by the initiation in 2001 of the Aurora program, which targets a potential human presence on Mars by 2025 [3]. Potential roles for Europe as a whole, via the European Space Agency (ESA) and with individual European countries, might include launch; the development, construction, and operation of both human and robotic spacecraft; the provision of instruments for U.S. spacecraft (or vice versa); and the provision of crew members. This latter point is, of course, the primary incentive for any potential partner to participate in the overall enterprise. The long history of NASA cooperation with ESA and European countries suggests that further such cooperation is potentially available.

Like Europe, Japan has a long history of cooperation with the United States, beginning before the local development of the N-1 launch vehicle based on American technology. Japanese interest in lunar exploration is evidenced by previous and planned probes to the Moon, although the Japanese long-range plan developed several years ago specifies a robotic lunar base as a goal and does not address human activities beyond Earth orbit. The Japanese are potentially capable of providing cooperative development of spacecraft and instruments, as well as providing launch capacity and crew members.

Russia has a long history of interest in human lunar and Mars exploration, a history that actually predates the beginning of the Space Age. This interest continues to this day with active study of human Mars missions in the context of an international program and development of an unmanned Phobos Sample Return project. Russia's ability to invest resources in space activities has, however, been significantly curtailed since the collapse of the Soviet Union. Nonetheless, as recently as 12 April 2004 (Cosmonautics Day), Russian President Putin said, "everyone in the leadership of the country understands that space activities fall into the category of the most important things" [4].

The Russian role in space exploration may be circumscribed by the country's present financial circumstances. Nonetheless, Russian rocket engines are among the world's best in terms of price and performance, and the use of such engines in the Atlas V vehicle family provides a basis for suggesting that any "heavy-lift" capability required in the future could quite likely benefit from the use of Russian engines or engine technology. Russia has provided consistently reliable human space transportation since the beginning of the Space Age; as this is written, Russian vehicles offer the only operational means of human space transportation to the ISS. Their architectural approaches are very different from those of the U.S., featuring long-term use of working systems and robotic testing of human systems. Such approaches may be relevant for international human Moon and Mars mission planning. Russia also has considerable experience with extended duration human space missions and much more recent experience than the United States with nuclear rockets and with the use of nuclear power in space.

China is, after the United States and Russia, the third country to have developed an indigenous human space flight capability. At present, the Chinese capability is limited both by lift capacity and by the relative immaturity of their technology, which has so far achieved only one human space flight. The Chinese have, however, indicated that they hope to develop a Mir-like space station by 2010 and plan to launch robotic lunar probes in the same time frame; this latter endeavor is potentially cooperative with U.S. goals.

Leaving aside the issue of potential roles, a central concern with regard to international cooperation on a program that will last decades is whether potential partners are even interested. In part, this may hinge on how the ISS partners view the eventual outcome of that project. Thus, a seemingly successful outcome of that effort may affect significantly both the willingness and the ability of other nations to join a U.S. Moon-Mars program. If the continuing cost of the ISS is a significant burden to other countries, that cost alone may mitigate against participation in further human exploration of the solar system.

We emphasize here that, in our view, successful completion of the ISS to meet international partner commitments is required. We are proposing—subject to partner agreement—an alternative means of meeting these commitments, based on early CEV development and Shuttle retirement and on the use of other launch assets to deliver the international modules to orbit. We believe such a scheme offers the several advantages of reducing cost, enhancing crew size, and providing earlier partner access to the ISS.

2. Dependence on International Partners

NASA traditionally has organized international cooperative programs so as to avoid having any partner on the "critical path"; that is, the foreign contribution was additive or complementary to the core U.S.

effort. Under direction from the NASA Administrator, this policy changed in the 1990's with respect to the International Space Station. Russia's contributions to the ISS clearly are essential to the effort as a whole, especially in view of the previously noted U.S. dependence on Russian launch capability for both crew rotation and cargo resupply following the *Columbia* accident. Whether this or a similar dependency would be acceptable in the context of a larger program of solar system exploration is a matter that can be expected to provoke considerable debate. Some will argue that the United States must be prepared to "go it alone" with its own core program in the event that any given partner elects to end its participation in the venture. Others will espouse the view that such a situation is not a true partnership at all, that the partnership is in fact forged by the necessity of mutual dependence.

3. Regulatory Concerns

Significant international partnership in the Exploration Initiative will be impeded and in some cases prevented if the current U.S. regulatory environment continues to apply in the future. Export control laws applicable to commercial technology, the Iran Non-Proliferation Act, and the International Traffic in Arms Regulations (ITAR) present an interlocking web of regulation and procedures designed to prevent technology transfer—particularly aerospace technology—from the United States to other nations. In many cases, this purpose has become moot; numerous international competitors have technical capabilities comparable to, or exceeding, those of U.S. firms and are occupying niches formerly dominated by U.S. companies.

Nonetheless, several high-profile, high-penalty cases in recent years have driven home to U.S. firms the absolute necessity of observing these restrictions and, where ambiguity exists, adopting conservative interpretations of them. Many aerospace engineers and space scientists can cite "war stories" highlighting the difficulty of forging effective international partnerships under these circumstances. Without significant changes in the existing regulatory framework, it is difficult to imagine a technically rich international partnership in a new exploration enterprise.

Safety and Exploration Beyond LEO

A total of 21 astronauts and cosmonauts have been lost in the course of 43 years of space flight operations (on space flights or in ground tests while preparing for space flight), including the *Columbia* crew a little more than a year ago. This properly raises concerns about the level of safety that human explorers can expect when they once again venture out of LEO. How do the risks of leaving Earth orbit compare to those experienced during launch or aboard the International Space Station? What standards of safety should we set as we explore destinations like the Moon, the Lagrange points, the near-Earth asteroids, and Mars?

Thirty-two years ago, the United States completed six history-making expeditions to the Moon. The Apollo Program was driven by the imperatives of the Cold War and President Kennedy's "before the decade is out" deadline, but engineers still were able to design a system they thought had a high probability of returning its crews safely to Earth. Apollo's stated design goals were to have a 0.999 probability of returning the crew safely and a 0.99 probability of mission success [5]. All system components were to be designed to meet those overall standards of reliability. The launch escape system, for example, combined with system redundancy gave the crew a variety of abort options. Although scheduling pressures, the breakdown of management controls, and a flawed safety process led to the tragedy of the Apollo 1 fire, a renewed focus on leadership and safe engineering practices produced a redesigned Apollo spacecraft that achieved the lunar landing without the loss of another crew. All crew members, even those aboard the crippled Apollo 13 spacecraft, returned safely to Earth, and six of seven lunar landing attempts were successful. Considering the technology of the day, the safety results were remarkable. New systems for exploration beyond LEO should aim for even higher levels of reliability and safely.

Human explorers heading for destinations beyond LEO will face more serious space hazards—as well as some new ones—than have astronauts on the Shuttle and the ISS. Those risk factors include a lengthy mission duration, a high-radiation environment, microgravity deconditioning, limited communications, numerous psychological stresses, and, eventually, working outside the spacecraft in harsh surface conditions. Additional risks arise as a result of the nature of the very thin logistics train that will be available to support the crew. If cargo resupply missions are included as an integral part of the architecture, reasonable redundancy in their provisioning must be planned. If it is planned for the crew to be able to operate for several years without support from Earth, this too carries certain identifiable risks. NASA should aggressively pursue parallel efforts to develop technical experience and countermeasures in all these areas so that crews face a manageable level of mission risk. The radiation hazard in particular is poorly understood today. Concerted efforts must be made to obtain data on the hazard and to develop effective countermeasures [6].

The *Challenger* and *Columbia* accidents have underlined the dangers facing space travelers and the consequences of ignoring our own human shortcomings in designing and operating spacecraft. We also have learned how resilient the American public is in facing these risks, as long as human space flight leaders are seen to be confronting and working to reduce them, and as long as the public supports the goals of such flights. The public recognizes that space flight is risky but will not tolerate mismanagement or willful disregard of astronaut safety. Another fatal accident caused by human negligence or organizational shortcomings would likely result in a lengthy American hiatus in human space flight. Although exploration is inherently hazardous, NASA must execute its reach into the solar system with the highest possible attention to safe crew return.

The *Columbia* and *Challenger* crews were committed to the advancement of our society's science and exploration goals; however, our space program over the past two decades has risked human crews for many missions that may have been more safely executed by robotic means. Astronaut explorers risk their lives whenever they venture into space. The exploration goals to which we commit them should be commensurate in importance with the inherent and significant risks of human space flight. This point was made by the Columbia Accident Investigation Board (CAIB): the risks undertaken in human space flight should be in pursuit of a goal worth attaining. The CAIB report makes it quite clear that continuing to fly the Space Shuttle to the ISS, with no definite purpose lying beyond, is not such a goal. Something more is required, and we believe that the program of lunar, Lagrange point, NEO, and Martian exploration discussed here provides precisely the goals needed.

Our experience with failure in human space flight should lead us to adhere, where practicable, to the following guidelines in the approach to a new exploration architecture:

- Manned launch systems must provide a launch escape/abort capability throughout the flight envelope.
- Cargo should be separated from piloted spacecraft to the extent that it is possible and reasonable to do so. Automated systems designed to meet upcargo requirements should be capable of supporting downcargo requirements as well.
- Robotic precursor missions should be employed to understand the environment and validate technologies and operations prior to initiating human missions.
- Intermediate mission milestones and destinations should be used to build confidence and experience before undertaking deep space voyages.
- Spacecraft should retain an abort capability to Earth or to a surface safe haven throughout their transit phase.
- Exploration infrastructure should evolve to maximize opportunities for redundant and emergency operations.

Both the astronauts and the public understand the risks of space flight and recognize that great discoveries merit the acceptance of danger. Our obligation in any new exploration vision is to ensure that our destinations and goals are worthy of the risks that await us among the planets.

The Shuttle and the International Space Station

Attributes of the Shuttle

The Space Shuttle has performed for more than 20 years as the workhorse of America's human space flight effort. It is the world's first reusable spaceship, and its capabilities for large payload delivery and return, orbital maneuvering and rendezvous, and robotic and EVA operations are still unmatched by any other system. The Shuttle's flexibility and large cargo capacity have made it the linchpin for assembly of the International Space Station.

Two fatal accidents and 14 deaths in 113 flights have revealed weaknesses in the Shuttle's original design and raised significant concerns about its ability to operate safely for another decade or more. In our view, major changes to the Shuttle's design to improve crew safety dramatically (most significantly, a capable escape system) cannot be implemented easily. In addition, the Shuttle's high operating costs under continued tight NASA budgets consume funds that might be better devoted to new launch and exploration systems.

Given the unique capabilities of the Shuttle (delivery and berthing of large payloads, robotic and EVA capabilities, large down-mass capacity), its return to flight is imperative for rapid completion of the ISS. The tailoring of most completed ISS hardware for Shuttle launch argues for keeping the Shuttle operational until delivery of international partner modules. However, most ISS logistical needs might well be met using partner assets like the Russian Progress and the ESA's Automated

Transfer Vehicle (ATV). We see the Shuttle as essentially important to the ISS only for delivery and assembly of major flight hardware. Once completed, the ISS should shift to simpler, cheaper, and newer systems for logistics and crew support.

The Shuttle budget for FY2004 was nearly $4 billion [7]. If the Shuttle continues to fly beyond 2010 due to delays in return to flight or in ISS assembly, these funds will not be available for future exploration efforts. Moreover, as the CAIB report has made clear, if Shuttle flights are extended beyond 2010, recertification of the fleet will be required, an inevitably expensive and time-consuming process. For these reasons, we agree with the directive that once the ISS is complete or, as we have outlined here, possibly even at the "U.S. Core Complete" stage, the Space Shuttle should be retired [8]. NASA should also focus on options for supporting and completing the ISS using new U.S. cargo and launch systems, or international systems, that may be available around 2010 and that also have utility for beyond-LEO exploration (e.g., the new CEV and Shuttle-derived HLLV, Ariane, and Proton, and heavy-lift versions of the EELVs).

ISS Status and Utility

Since *Columbia*'s loss early in 2003, the ISS has been in caretaker status, maintained and operated by two-man crews launched and returned on the Russian Soyuz. Assembly has halted, and scientific work is at a low level due to manpower limitations and a limited cargo up- and down-mass capacity. NASA estimates that at least 23 and perhaps closer to 30 Shuttle launches would be required to complete the ISS (through the delivery of international partner laboratories). The agency also estimates that ISS completion will take at least five years from the date that Shuttle flights resume (now no earlier than March 2005). Some lessons from the ISS have already made valuable contributions to our future exploration planning. In its sixth year of orbital operations, the ISS has demonstrated the technical feasibility of complex orbital assembly. It has begun to generate some of the human health and productivity data we will need to plan longer voyages. Its technology may in many cases be adapted to exploration use (e.g., life support, pressurized volumes, logistics modeling, and on-orbit maintenance). We suggest a concerted effort by NASA to complete just such an assessment: What on the ISS is really applicable to deep-space missions? Knowing this answer before we proceed to Stage 2 will be essential if the most expeditious and economical program plan is to be developed.

Although the ISS does not figure prominently in the Exploration Vision beyond about 2016, it will nevertheless be important to the success of that effort. Its completion is an important milestone capping the success of the ISS partnership; walking away from the program would create huge difficulties in garnering international participation in the Exploration Vision. The President has also made the ISS the focus for at least a decade of orbital research aimed at understanding and solving the problems posed by long-duration space flight: microgravity debilitation, crew mental health and productivity, limited communications, the effects of partial G, and, to some extent, radiation exposure. One important capability the ISS currently lacks is that of housing larger crews of four to seven astronauts, necessary for evaluating crew dynamics and determining the best crew size and skill mix. Also, the current limitation of six-month crew stays should be extended in preparation for human interplanetary flight.

The ISS orbit offers few, if any, advantages for orbital assembly of future exploration vehicles due to the payload penalty incurred when launching to its high inclination, as well as the penalty exacted by this orbital inclination when departing to other destinations. But the Station's intelligent use and evolving partnerships greatly improve the prospects for the success of the first human expeditions beyond Earth-Moon space.

Launch Vehicle Options

The Exploration Initiative will create extensive, and in many cases unique, demands for launch services. Only a subset of these can be satisfied with the existing global fleet of expendable launch vehicles (ELVs), and even then their cost-effectiveness will be a major issue. Although it might be possible to return to the Moon using a combination of such assets together with on-orbit assembly, a realistic Mars exploration scenario will require the re-establishment of heavy-lift launch capability or the development of greatly advanced in-space propulsion technologies that would reduce the "mass-to-LEO" delivery requirements.

Our study findings concur with the growing consensus that crew missions to orbit present more stringent safety and reliability requirements than bulk cargo shipments, and therefore a mixed-fleet approach is the most appropriate path to pursue. Under this scenario, an initial CEV configuration could and should be delivered to LEO by highly reliable, human-rated launch systems. To the extent possible, these same systems should be employed for high-value or critical hardware elements, such as interplanetary transfer vehicles, surface habitation modules, landers, and nuclear power systems. As discussed below, such launch systems can be derived from present and soon-to-be operational vehicles. This would include Delta IV and Atlas V in the domestic market, with the Proton and Ariane V being readily available international alternatives. The Long March and H-IIA upgrades will need extensive political and technical preparation before they can be regarded as viable alternatives for high-value cargo.

By contrast, bulk cargo such as propellant, life support system consumables, and radiation shielding should be manifested on significantly larger vehicles, the designs of which are intended to reduce costs through economies of scale and commonsense relaxation of reliability requirements. For example, the elimination of crew emergency abort capability will by itself generate numerous cost-saving opportunities.

U.S. Expendable Launch Vehicles

The Delta IV and Atlas V families of Evolved Expendable Launch Vehicles (EELVs), developed in part under Air Force sponsorship, are the most obvious U.S. candidates for supporting the crew and high-value hardware launch activities. These are modern launch systems with state-of-the art launch facilities as well as healthy supplier and manufacturing support infrastructures. Furthermore, the collapse of the commercial communications satellite market has resulted in surplus capacity for both systems. An exploration agenda that exploits this capacity should attract the backing of EELV stakeholders. The biggest challenge may be to leverage the EELV capability without absorbing an excessive share of the massive EELV program overhead. We recommend that NASA pursue multilaunch procurements, the cost-effectiveness of which was first demonstrated by the USAF in its block-buy of Delta II vehicles for launch of the GPS satellite constellation.

Technically, evolving the EELV fleet to carry a capsule-like CEV would appear to be a straightforward engineering task, but not so for the earlier winged Orbital Space Plane configuration that would have induced unique torques and lateral loads at the payload interface. A more significant issue could be the launch infrastructure enhancements that will be required to provide crew access and emergency egress from a CEV during the terminal count.

As mentioned earlier, we have concluded that in addition to Atlas and Delta, another CEV launch option merits further consideration. This option is based on the development of a new launch system that combines a cryogenic upper stage with a single Shuttle SRM. This approach has several attractive features. It allows us to take advantage of the existing Shuttle human space flight assets at the Vehicle Assembly Building (VAB) and Launch Complexes 39A and B that would otherwise become idle upon termination of Shuttle operations. Furthermore, the SRM has proven to be the most reliable launch vehicle in the history of manned space flight, with no failures in 176 flights following the modifications implemented in the aftermath of the *Challenger* accident. Finally, the reusability of the SRM when operated independently of the Space Shuttle could result in significant cost savings relative to fully expendable vehicles. A sketch of such a new launch vehicle is provided in Fig. 1, courtesy of ATK Thiokol.

SRB, in-line, medium lift candidate for CEV launch.

Foreign Launch Vehicles

Several foreign launch systems can provide essentially the same level of medium-lift capability as Atlas and Delta. Under the current political environment, Ariane V launches from Kourou, Proton operations at Baikonur, and Sea Launch Zenit flights from the Odyssey platform in the Pacific are the most readily available options for CEV-class missions. Ariane V offers the fewest regulatory impediments to U.S. users, and it is reasonable to suppose that any French or European participation in the Moon-Mars initiative will feature a role for this launch system. Furthermore, the Ariane Transfer Vehicle (ATV) should be adaptable to other roles besides ISS servicing. Also worth noting is the added flexibility and redundancy that could be achieved by launching human missions from Kourou. Such a capability could become available in several years with very little effort, once the planned Kourou-based Soyuz launch operations are underway.

Sea Launch presents an unusual situation due to its multinational makeup. Although it is headquartered in and operated from Long Beach, California, the Sea Launch organization must comply with ITAR and the other related regulatory requirements and constraints mentioned earlier. In many ways this makes Sea Launch a foreign entity as far as domestic users are concerned. Congressional action will be necessary to modify the existing body of regulation to facilitate use of this asset in the Exploration Initiative.

Such participation by Sea Launch would require several technical changes to present operations. First, a CEV delivery to the ISS would utilize a two-stage Zenit comparable to the original Zenit-2 instead of the Zenit-3SL that is employed for geosynchronous orbit missions. Furthermore, the potential exists for conducting such ISS missions much closer to the Sea Launch base of operations in California. It is also worth noting that the Sea Launch consortium has been pursuing commercial launch opportunities at Baikonur for several years. Should this capability materialize, it will provide additional flexibility and synergy with ISS servicing missions.

If political constraints can be resolved favorably, several additional international launch options would become available for exploration applications. The Chinese Long March (Chang Zheng) family has a proven track record that now includes the safe launch of a human space mission. Several current and future Long March vehicle configurations appear to have more than adequate performance for CEV-class missions, and it is likely that their prices would be competitive with those of Western launch providers.

Shuttle-Derived Vehicles

There are basically three options for Shuttle-derived vehicles (SDV). The CEV/SRM option has been discussed briefly above but has not been studied as a serious launch option. This is likely due in part to the relatively recent (i.e., post-*Columbia*) emergence of capsule designs as credible contenders for the CEV mission.

In contrast, NASA and its associated contractors spent considerable energy assessing alternative heavy-lift Shuttle derivatives during earlier Space Station redesign efforts. The most widely known so far has been the so-called Shuttle-C configuration, in which the Orbiter would be replaced by a functionally equivalent stage from which crew systems have been eliminated. Such a stage might or might not be recoverable. In the latter case, consideration would need to be given to substituting expendable, lower-cost RS-68 engines for the SSMEs (an option not available during the earlier trade studies). The most attractive aspect of this option is the relatively small number of modifications and non-recurring investments required to reach operational capability. However, the basic Shuttle-C design thus retains many of the unattractive features of the Shuttle as a payload carrier, including unusual mating configurations and side-loading. Such features might be acceptable if the Shuttle-C were to be used for completing ISS assembly, since many of the remaining ISS payloads are already configured and qualified for these environments.

Perhaps the worst feature of the Shuttle-C from an exploration perspective is the fact that the sidemount payload carrier configuration is exceptionally wasteful of intrinsic lift capacity. The payload carrier is essentially a Shuttle Orbiter without wings or a crew compartment, and it is therefore quite heavy, with a very high recurring cost, on the order of $500-600 million per flight. The sidemount configuration would not evolve easily into a more capable design, a time-honored practice with most other launch vehicles.

In contrast, a more conventional in-line SDV design, in which the payload is mounted to the top of the External Tank, would require more initial effort to implement but would provide numerous operational and performance benefits, the most significant of which is greater payload mass. Again, the SSMEs would be replaced by RS-68 engines (or production versions of the SSME) mounted to the base of the External Tank, as with the Energia booster configuration. Although most effective for exploration cargo missions, the in-line design would likely require significant modifications to existing ISS hardware element mounting arrangements, which, as noted above, have been designed and qualified for the Shuttle Orbiter payload bay.

New Heavy-Lift Launcher

An entirely new heavy-lift launch vehicle is absolutely necessary only if the most efficient mission architecture dictates that payloads on the order of 200 metric tons to LEO are required. At that point, the safety-related issues associated with such a large vehicle could render it incompatible with existing U.S. launch ranges.

A new launcher optimized for cargo, akin to the old "big dumb booster" concept, could achieve significant operational savings over an SDV. Comparisons are particularly interesting for lox/hydrocarbon vehicles incorporating high-performance engines similar to the RD-170/171 and RD-180 family, or all-solid configurations based on clusters of SRMs. However, the investment in both vehicle and ground infrastructure development make this the most expensive option in terms of non-recurring costs. Furthermore, as there is no other perceived use for such a vehicle, it would have to be sponsored and maintained entirely by the Exploration Initiative.

Consequently, unless a truly revolutionary launch vehicle technology can be identified, one that leapfrogs current system capabilities, it is difficult to make the case that an entirely new system is needed.

Conclusions and Recommendations

The nation has three or four technically viable domestic launch options for alternative crew access to low Earth orbit in the near term. The selection of one or more on approaches ultimately may depend more on political factors than on cost. For example, will it be acceptable to use a Delta IV or a Sea Launch Zenit-2 to launch astronauts to the ISS if it means closing the VAB and Launch Complexes 39A and B?

On a global level, there are many reasons to make the CEV compatible with as many launch systems as possible. Technically, such redundancy will help avoid the single-point failure vulnerability of the Shuttle system that is currently paralyzing ISS operations. Second, those participants who wish to develop and utilize their own human launch capabilities are more likely to continue to be committed partners during difficult periods. Finally, selling CEVs to the rest of the world could become a notable export opportunity and would enable the United States to retain the lead with respect to defining standards and guiding human launch vehicle operations around the world. The F-35 Joint Strike Fighter program may serve as a model in this regard.

At this point, SDV designs including both an SRM-based vehicle for CEV services and an in-line heavy-lift configuration appear to be very attractive options for leveraging the investment in infrastructure and people for a quick response. The manner in which the Shuttle phase-out is actually implemented and the determination of which infrastructure elements will then be available for other applications will be major determining factors in whether these vehicles can become viable options for near-term applications.

Steps and Stages

Departing Low Earth Orbit

The launch vehicle options discussed in the prior section can do no more than deliver desired payloads to low Earth orbit. The desire to go beyond LEO invites consideration as to what mission design, or designs, might be most effective, and what the criteria for such effectiveness might be.

Regardless of the chosen mission architectures, any mission to Mars (or even a substantive return to the Moon) will require the use of a "staging area," or "assembly node," to marshal the various vehicles and systems that are required. Although the Apollo landings were executed without such assembly, it is noteworthy that the Saturn 5 launch vehicle developed for the program was capable of placing a payload of about 140 metric tons in LEO, somewhat larger than can be obtained from any of the approaches discussed in section 4, save possibly the "clean sheet of paper" design. Even the Saturn 5, using the lunar orbit rendezvous technique, was able to deliver only about 35 metric tons to low lunar orbit, and 8 metric tons to the lunar surface. This provided a bare minimum of mission capability (e.g., six man-days on the lunar surface for the longest missions). In all likelihood, something more will be desired for future lunar missions, so it will be necessary to assemble larger payloads in an appropriate location. It is equally clear that a Mars mission will require at least several hundred metric tons at the assembly node.

Construction of the ISS has given us considerable experience in the modular assembly of large vehicles in LEO, and it is only natural that a LEO assembly node would be considered for deep space missions. Assembly in LEO may well become the method of choice; above all else, it offers the advantage of a staging area only a few tens of minutes from home. Any LEO assembly node also possesses several important disadvantages, and some orbits are considerably less desirable than others.

A given rocket launched from a given site will be able to place a larger payload into a lower-inclination (i.e., near-equatorial) orbit than into a higher-inclination (i.e., near-polar) orbit. Neglecting overflight exclusion zones for range safety considerations, a rocket launched from any site can achieve the maximum possible inclination of ±90° (a polar orbit), but the lowest achievable inclination from a specified launch site is equal to the latitude of the site and is achieved by means of a due-east launch from the site. (Slightly lower inclinations may be attained, with some loss of efficiency, by means of a "dogleg" maneuver, in which the vehicle first flies toward the equator, then turns east.) Easterly launch from a low-latitude site is further advantageous in that the rocket can take advantage of the Earth's rotational velocity, which is greater for a lower-latitude site. Thus, near-equatorial launch sites such as Kourou are favored in two ways: the full range of orbital inclinations (±90°) can be attained, and more mass can be placed in orbit. Launch sites such as Baikonur, at approximately 50° North latitude, and Vandenberg, which is at approximately 35° North latitude but has significant overflight constraints for easterly launches, are greatly disadvantaged in this respect.

If it is politically necessary that the launch sites of all spacefaring nations be able to access the chosen LEO assembly node, then the node must be in a high-inclination orbit, and the mass of any payload delivered to that orbit will be degraded by 10-20%, depending on the site latitude and the design of the launch vehicle. (Use of an equatorial launch site does not eliminate this penalty when launching to a high-inclination orbit.) This will have a measurable economic impact on the Exploration Initiative. During the time frame addressed by this report—the next several decades—the cost of access to Earth orbit can hardly be less than several thousand dollars per kilogram, and, as we have discussed, even a Spartan expedition to Mars will require many hundreds of metric tons of material to be delivered to LEO. It is easily seen that the cost of using a high-inclination LEO staging area will be substantially higher than it would be at lower inclinations. Other physical constraints exist as well. To depart for the Moon or Mars from a staging area in LEO requires, among other things, that the orbital plane of the assembly node contain the departure direction during the available launch window. If this geometrical requirement is not satisfied, an expensive and quite possibly prohibitive orbital plane change will be required.

Departure from low Earth orbit to Mars (or another destination beyond the Earth-Moon system) requires that the departure vector be very nearly tangent to Earth's orbit about the Sun during the launch window, a period of a few weeks duration every 26 months for the most favorable opportunities. If the plane of the LEO assembly node is not so aligned as to contain the departure vector as discussed above—and the probability of such an alignment is low unless the node is placed in an orbit selected, well in advance, to favor a particular opportunity—then the mission cannot leave Earth orbit. The rapid nodal regression—several degrees per day for moderate inclination low Earth orbits—may restrict the usable portion of the window even further.

For travel to the Moon, or to the Earth-Moon Lagrange Points (e.g., EML1), departure opportunities from a LEO node occur roughly every two weeks. For the Sun-Earth Lagrange Points, opportunities would occur less often.

Although no LEO node can be optimally located for travel to both the Moon and Mars, or even to either destination all the time, near-equatorial orbits are heavily favored in terms of performance as compared to higher-inclination orbits because the required plane changes to reach the desired destination will be smaller.

In summary, departing from Earth orbit can result in plane change penalties, will substantially restrict the available departure times, and will place restrictions on other conditions. This is not the case when launching from the surface of the Earth, where the planetary rotation provides access to any required launch plane orientation at least once per day.

This conclusion provides the rationale for the use of the Lagrange Points, either Earth- or solar-referenced, as staging areas in cislunar space for travel to the Moon or Mars. Use of these locations also involves performance penalties, but they are typically less than those for plane change maneuvers and are consistent over time, freeing the mission architecture from critical dependence on specific launch window constraints.

In this vein, very high Earth orbits (HEO) may become attractive as staging area locations. The required plane change to the target inclination can be accomplished quite cheaply, at the apogee of the LEO-departure transfer orbit. Nodal regression for high, near-equatorial orbits is negligible, so the staging area will remain useful throughout a given launch window and for multiple opportunities.

Electric Propulsion

If an HEO assembly node, including a node at EML1, is selected, it is possible to substantially improve the mass delivery efficiency of the architecture. The assembled vehicle, or more likely sub-elements of it, can be delivered to the higher orbit perhaps several months before departure for the Moon, Mars, or an NEO, at a time when the orbit plane orientation will be correct for the anticipated departure.

The higher orbit can be reached efficiently using low-thrust electric propulsion (EP). This would require several months, but once in high orbit a crew could rendezvous with the assembled vehicle, departing either from Earth's surface or from LEO. Then, chemical propulsion could be used for the remainder of the outbound mission at a fraction of the requirement for LEO departure, allowing a shorter trip. For departure to Mars, a dual propulsion system may be useful, with chemical propulsion used for fast departure and arrival, and electric propulsion used during the several months of interplanetary travel. Solar-electric propulsion (SEP) has been considered for operations in cislunar space, and nuclear-electric propulsion (NEP) is useful irrespective of proximity to the Sun.

Like all space propulsion schemes, electric propulsion requires the generation and expulsion of a directed mass flow from the vehicle, which is then accelerated in the opposite direction, according to Newton's 3rd Law of Motion. However, EP employs a different fundamental mechanism for transferring energy to the fluid stream than do chemical rockets (or even nuclear thermal rockets, discussed below). Through the mechanism of the converging-diverging supersonic nozzle, chemical rockets are devices for converting the thermal energy of combustion into a highly directed propellant stream. With EP, the electrical energy is used to strip electrons from the atoms of an easily ionized, preferably heavy, element (e.g., xenon). The heavy positive ions are then accelerated in an electromagnetic field and ejected from the back of the "rocket" in a stream of high speed particles. (The previously stripped electrons must be allowed to recombine with the ions as they exit to prevent buildup of a net charge on the spacecraft.)

The major advantage of EP is the fuel efficiency it offers; a specific impulse in the range of thousands of seconds is easily achieved. However, EP systems offer very low thrust, several orders of magnitude below that of chemical propulsion systems. Moreover, a large mass of hardware is required to generate this thrust, nullifying to some extent the efficiency of the basic engine; much of the presumed payload advantage of EP systems is used to accelerate the mass of the powerplant.

The feasibility of large-scale nuclear electric propulsion is likely to be demonstrated first during the Jupiter Icy Moons Orbiter (JIMO) mission, a robotic mission currently planned for launch in 2015

[9]. The mission is anticipated to use a reactor in the range of several hundred kilowatts and to require a mass of some 20 metric tons in LEO, of which 10-13 metric tons will be xenon fuel, the favored choice for such a system. The actual science payload is projected to be in the range of 1,500 kg; much of the remainder of the overall mission mass is absorbed by the hardware (reactor, energy conversion system, radiators, structure, etc.) required for the NEP system.

Human missions will require megawatt-class reactors and comparable increases in the mass of fuel required. The availability of xenon in such large quantities could be in question. Xenon is present in trace amounts in the atmosphere and is extracted in the course of liquid oxygen and nitrogen production. Current world production of xenon is on the order of 10 million liters per year (59 metric tons at standard temperature and pressure), at an average price of about $10 per liter, or about $1,700 per kilogram [10]. Unless substantial progress is made in this area, use of a less desirable fuel will be necessary.

Nuclear Thermal Propulsion

Of the technologies so far proposed for radically transforming the architecture of Moon and Mars exploration, nuclear thermal propulsion (NTP) is among the most credible in terms of both fundamental physics and engineering development maturity. NTP is based on the direct transfer of fission-generated heat from a solid nuclear core (we omit here any discussion of gaseous core nuclear reactors) to a working fluid (hydrogen) that also serves as the propellant. By contrast, with NEP the original thermal energy undergoes several conversions, and therefore losses in overall efficiency, before being imparted to xenon or some comparable propellant via electric or magnetic fields.

NTP is attractive because of the high thrust level it can provide, similar to that of conventional chemical rockets and several orders of magnitude greater than NEP. For maneuvers within planetary gravity wells, particularly Earth escape, such high thrust can reduce transit times from months to hours. Although NTP is not as fuel-efficient in terms of specific impulse as NEP, the reduced trip time to and from Mars offers significant benefits in terms of reducing the crew exposure to microgravity and radiation, while at the same time reducing requirements for consumable supplies.

The major advantage of NTP compared to chemical propulsion is that the energy contained in the exhausted propellant (a key factor in determining a rocket engine's maximum potential performance) is not constrained to the energy available from the chemical combustion of a fuel and an oxidizer. The hydrogen exhaust from an NTP engine can be hotter than for chemical propellants, limited only by the thermal tolerance of the engine materials themselves. Also, the lighter molecular weight of the pure hydrogen exhaust greatly improves the overall operating efficiency. These effects together offer essentially double the 450 seconds of specific impulse typical of a high-performance lox-hydrogen upper stage engine. With such enhanced performance, the amount of propellant needed for the mission can be reduced by more than half, with a concomitant reduction in launch costs.

The advantages of NTP are mitigated by numerous material compatibility issues. The heated hydrogen tends to erode the reactor fuel core, and as with any nuclear reactor there is a high level of high-energy radiation emitted, which severely constrains the design and configuration of the overall vehicle.

Also, although the higher specific impulse does offer the capability to carry more payload or less fuel, the improvement in overall performance as compared with chemical propellants is not as great as might be suggested from consideration of the improved specific impulse. Because of the weight of the reactor and associated structure, the overall thrust-to-weight ratio of an NTP system will be substantially poorer than for a chemical system, nullifying part of the presumed payload advantage. Even with these reservations, the potential of NTP as a tool in the exploration of the solar system is enormous, and it has been recognized as such for decades.

Because of this potential, the U.S. Atomic Energy Commission (the predecessor to ERDA and thence DoE), and then NASA, invested significantly in NTP development during the 1950s and 1960s, with projects known as Rover and NERVA (Nuclear Energy for Rocket Vehicle Applications). These efforts resulted in the development and testing of multiple reactors and rocket engines at the Nevada Test Site. These tests validated the general operational feasibility of NTP by 1973, when the effort was terminated as part of the overall retrenchment from human space exploration after Apollo [11].

Arguments concerning performance aspects of NTP relative to other options are as valid today as they were in 1972. However, the social environment for conducting technical R&D related to nuclear systems has changed dramatically, making any such task much more difficult than in earlier decades. International treaty obligations preclude the open air testing techniques employed for the original NTP testing, while public opinion is far less tolerant of any nuclear systems. Moreover, the government and industrial nuclear infrastructure has atrophied considerably in the last 30 years as a result of the demise of commercial nuclear power and the end of the Cold War.

As discussed in connection with NEP, NASA is beginning to resurrect nuclear propulsion options in general. The capabilities now under development through Project Prometheus in preparation for NEP missions such as JIMO can also help lay the foundation for a more extensive program that includes NTP. However, unlike NEP, NTP can be justified only for human missions, where there is major benefit to be obtained by reducing trip time and increasing payload.

Our team endorses these, and stronger, efforts by NASA, because nuclear power and propulsion is ultimately necessary for the exploration of the solar system. At the same time, however, very effective missions to Mars clearly can be designed using the combination of chemical propulsion for departure from Earth and for return from Mars, and aeroassist upon arrival at Mars and when returning to Earth. The mission architecture can be made substantially more efficient by extracting propellant from the Martian atmosphere, which eliminates a substantial part of the logistical burden, although of course a production plant must be pre-emplaced. Nuclear propulsion, though desirable, is thus not essential for the exploration of Mars.

Nuclear power is a separate and initially more critical issue for the exploration of both the Moon and Mars. Mars' distance from the sun degrades the output of a given solar array by a factor of approximately 2.2, making the generation of useful surface solar power a rather cumbersome affair, one that is further compromised by the accumulation of dust on the panels. The two-week lunar night poses an even greater design challenge for lunar missions if they are to remain through the night. The compelling solution to these problems is the development of space nuclear power reactors, a solution we consider to be essential to implement.

Interplanetary Cruise

Many options have been proposed concerning classes of trajectories that may be used for travel between Earth and Mars. These include the Aldrin cycler concept, as well as other types of cyclers, and the use of Venus flybys. But chemical propulsion is suitable for six- to eight-month transits from a high Earth orbit to a high Mars orbit, such as EML1 to Phobos or Deimos. This avoids the high Δv requirements to achieve a low circular orbit. If only chemical propulsion is used, the transfer vehicle will have to refuel at Mars. If a combination of chemical and electric propulsion is used, a round trip may be possible. The same is true if a chemical-aerobrake mission design is selected. But certainly cargo vehicles will be needed and, if missions are not time critical, these vehicles could be operated with low thrust alone. Of course, the infrastructure for continuous operations, as with the various cycler concepts, would have to be developed at Earth and placed at both planets.

Human Factors

Many of the human factors important to long-duration space flight outside the protection of the Earth's magnetosphere can be addressed in long-duration missions on the ISS. The principal exception is in the area of radiation exposure in interplanetary space, where Earth's magnetic field is not available to deflect most of the energetic solar particles and some of the lower energy cosmic rays. Various areas of concern will be discussed below.

Gravitational Acceleration

Humans have evolved in our present gravitational environment of "1-g," about 9.8 m/s^2, for many millennia. At the dawn of manned spaceflight, 45 years ago, there existed real concern as to how the human body would respond to the near-weightless environment of space flight. Experience in both the U.S. and Soviet/Russian space programs, for durations of up to almost 15 months, has shown that most physiological systems adapt quite well to low gravity within days or weeks and then return to normal upon return to Earth. The principal exception is in "mineral balance," especially the calcium in human bones, which relates to their strength and resistance to fracture. So-called "bone loss" remains a serious problem, and NASA continues to pursue research in this area as a high priority.

Part of the difficulty in studying this problem lies in the low rate of mineral loss, comparable to that observed in bed-rest studies on Earth. The issue is further complicated by the normal decrease in mineral content of adult bones with aging. The ultimate concern for some is the risk of weight-bearing bone fracture upon return to Earth after several years in weightlessness. It is reassuring to note that, after all the long-duration flights to date in Skylab, MIR, or the ISS, there have been no fractures of weight-bearing bones for any astronaut or cosmonaut after returning to Earth.

Still, some argue for more positive preventive action to eliminate the slow mineral loss that has been observed. Dietary and pharmacological studies continue to be pursued. Exercise protocols that provide compression stress to the leg bones, such as an in-flight treadmill with crewmembers anchored by bungee cords, have been employed with positive results. The ISS currently employs the Interim Resistive Exercise Device (IRED) to enable crews to load muscle and bone with vigorous strength training exercises. The IRED has shown some initial promise in slowing bone loss. Finally, a large rotating structure has been envisaged that can provide variable acceleration levels by centrifugal force. Whether or not this is required will have to await more studies on the ISS;, if required, such a structure will be a major design effort for the interplanetary spacecraft.

In summary, numerous problems and inefficiencies result from the microgravity environment. Relative to the overall scope of an expedition to Mars, however, they are inconveniences rather than show-stoppers.

Radiation

The biological effects of radiation in the space environment currently have an estimated uncertainty factor of about four [5]. Radiation biology is clearly a very important factor in the design of interplanetary spacecraft, but with such large uncertainties in the effects of radiation, we must await further research and the development of expert understanding before definitive design rules can be developed. Lacking such, there is much that can be done by designing spacecraft to contain “storm shelters” for protection against energetic solar protons. Hydrogen is one of the best materials for such shielding; likely the storm shelter will be a central region of the spacecraft surrounded by water tanks and possibly some degree of magnetic shielding from heavier and more energetic galactic cosmic rays. Pharmacological protection is also being considered. NASA should expedite radiation studies at dedicated accelerator facilities, and it should obtain accurate data about the radiation flux beyond the magnetosphere. At this point, we must assume that some combination of the various design approaches will be found to reduce the radiation risk to humans to an acceptable level for several years of interplanetary travel.

Social and Psychological Factors

The social-psychological aspects of crew selection, training, and in-flight problem resolution have been neglected for many years, particularly in the U.S. space program. In the early days of U.S. space flight, crews were small (three members or fewer, until the Space Shuttle arrived), potential selectees were few (usually fewer than 50 candidates for a mission were available in the Astronaut office), all had trained and worked together for many years (allowing them to become aware of the strengths and weaknesses of their crewmates), the selections for flight were made principally by senior fellow-astronauts (Chief of Astronaut Office and Director of Flight Crew Operations, who knew all flight crew candidates well), and mission durations were short (less than two weeks). In these circumstances, it was expected that compatible crews with little social-psychological friction should be the norm, and (with minor exceptions) this was found to be true.

However, as crews have become larger (six or seven members on a Shuttle flight) and included both genders, as well as those of different nationalities and professional backgrounds, often with restricted time available to train together, some increased psychological stress is to be expected. The minimal crew interpersonal friction encountered so far (at least publicly) is therefore a remarkable achievement. Credit should perhaps go to the high motivation of all crewmembers (some friction is simply overlooked or resolved), good selection of crews by senior astronauts and cosmonauts, and a command structure that makes each individual's responsibilities clear.

For future missions in interplanetary space, it is recommended that additional time be given to train a number of candidates together (at least a year), in several locations, before the final crew composition is determined. Possible locations for Mars mission preparation could include areas in the Arctic or Antarctic, the ISS if adequate transportation is available, or lunar missions of shorter duration, with technical and scientific work to be done. Social interaction with families of other nationalities should be included. A Russian proverb, publicly related years ago by cosmonaut Oleg Atkov, states roughly that "individuals should never undertake a difficult and risky task until they had consumed together 20 kg of salt." The obvious interpretation is that they should share many meals together, becoming well known to each other. Although difficult for mission planners to achieve, this seems to be the best way to ensure a smoothly performing, compatible mix of crewmembers for interplanetary missions.

System Design Implications

For these longer missions, human factors become increasingly important. Exercise facilities are essential to maintaining the good health required in flight, as well as at the destination and eventually for return to Earth. Additional training in medical care and procedures is important, especially if an MD is not included in the crew. Individual private video conferencing capability should be available for discussion of medical problems and especially for any treatment required. Social-psychological problem resolution, if and when required, should be handled on this private loop. Cross-skills training is mandatory because the number of crewpersons is expected to be rather small. Cross training ensures both availability of competent personnel and better understanding among crewmembers of the others work objectives. NASA should conduct studies to determine the needed skills for each destination planned. The ISS may provide a good training ground for some of these.

Food systems should be entirely pre-packed, as was done in the Skylab program more than 30 years ago. Although pleasant and enjoyable, fresh-frozen items can be omitted. Worth noting also is that radiation-stabilized foods can provide a very useful alternative to frozen foods for long-term storage. Onboard growth of foods is a research task appropriate to the ISS, rather than it being a critically needed operational system. Although freshly grown foods seem to have a positive psychological effect on long-duration flights on the ISS, their production should not be a mandatory requirement for continuing an interplanetary flight.

Artificial gravity via rotation of the entire space assembly is a major design consideration. If used, some large-radius, relatively slow rotation should be used to minimize coriolis forces. However, weightlessness (free-fall) has proven quite satisfactory on all previous long-duration missions, and the ISS will have provided much more experience before these interplanetary missions are flown. It therefore seems best to rely on a "free-fall" design until it is shown to be unacceptable for reasons presently unknown. It should also be noted that, to the extent that microgravity exposure is deemed a problem, faster transit times provide considerable relief. The additional design cost and complexity attendant to large, rotating spacecraft may well be better invested in nuclear propulsion systems, which, as noted above, allow significantly shorter transit times.

The Cost of Going to Mars

Seventy years of aerospace system development data show a strong correlation between the weight of aerospace hardware, properly segregated according to category, and the cost of its development. The NASA/Air Force Cost Model (NAFCOM) reveals the median cost for development of human-rated spacecraft to be about $420 K per kilogram and the median cost for the first production unit of such spacecraft to be about $29 K per kilogram. (FY 2004 dollars are used throughout this discussion.)

However, no human-rated spacecraft has been developed in the past 20 years. Further, the President's Exploration program does not reach the funding levels needed for a Mars program until 2014; thus, 30 years of productivity gains will have occurred before any such program begins. Assuming that it will require 10 years to develop the hardware to launch the first human Mars expedition, there will be another decade of productivity improvement before the spacecraft enters production. The above results must therefore be adjusted for the productivity improvements that have occurred and that will occur before the first Mars expedition could leave Earth. Because future productivity gains are unknowable, we will assume 2% annually for the entire period as a conservative estimate; this is lower than the level of productivity growth in the U.S. economy over the past 20 years.

Finally, we observe that the majority of human Mars expedition studies have found that about 500 metric tons is required in low Earth orbit for a mission based on chemical propulsion.

Development Costs

We can estimate the design, development, test, and evaluation costs for a human Mars mission by noting that, of the approximately 500 metric tons required in LEO at the outset of the expedition, at least 250 metric tons consist of propellant, with the remainder being the so-called "dry spacecraft," to which our hardware development cost estimate will apply. Assuming traditional NASA program management, but including 30 years of 2% productivity growth, we find that human-rated spacecraft should have a median cost of about $230 K per kg at the beginning of the 10-year development program in 2014. This results in a development cost estimate of $58 B, or an average of about $5.8 B per year over that 10-year period.

Production Costs

Again assuming 250 metric tons of human-rated spacecraft and accounting for 40 years of productivity gains before this spacecraft enters production, we estimate first unit production cost at about $13 K per kg in 2024. This gives a total first unit production cost of $3.2 B.

First Mission Cost

The direct cost of the first Mars expedition will be the cost of the human-rated spacecraft, the (negligible) cost of the propellant, and the cost of launching all the required mass to LEO. Observing that there has been no significant change in the *cost* of space launch over the past 40 years (we note that beginning about 1994, some sovereign competitors in the space launch business started *pricing* below cost), we will assume that the present launch costs of $9-11 K per kg will continue for the next 40 years. On this basis, we estimate the cost of placing 500 metric tons in LEO at about $4.4-5.5 B per mission. Summing these results, we conclude that the first human Mars Expedition will have a direct cost of around $7.6-8.7 B.

Subsequent Mission Cost

The production of aerospace hardware characteristically shows a "learning curve" of about 85% (i.e., each doubling of the production quantity results in a cost reduction to about 85% of the earlier level). Thus, the second set of Mars expedition hardware can be expected to cost about $2.7 B, the fourth set about $2.3 B, and so forth.

Summing this well-established effect over 20 years (9 missions to Mars) results in a total hardware cost of $20.9 B. Adding to this the $40-50 B for placing nine missions worth of mass into LEO yields an average mission cost, over 20 years, of $6.8-7.9 B. This result assumes that no new hardware development is initiated over the two-decade period between the first and ninth missions, which may be unrealistic.

Total 30-Year Cost

Summing the 10 years of development costs and mission execution costs for 9 missions over 20 years, we estimate a total program cost over the 30-year period 2014-2044 of $119-129 B. For comparison, the Apollo program cost about $130 B in FY2004 dollars spent over about a decade.

Sensitivity Analysis

Based on the above analysis, we can estimate the present value of using a nuclear thermal rocket instead of chemical rockets for LEO-Mars-LEO transportation. In addition to reducing the travel time, such a rocket can be expected to save at least 100 metric tons of propellant. This represents a savings of $0.9-1.1 B in launch costs for each mission. Discounting at the U.S. Government's 7% cost of money across the entire 40 year period (2004-2044) suggests that investment of up to $1.1 B is economically justified *today* if the development of a nuclear thermal rocket for a human Mars mission will save 100 metric tons of LEO mass, given current space launch prices.

We can similarly determine the economic value of lower space launch costs. Halving the cost of launch to $4-6 K per kg would result in a savings of about $2.5 B per human Mars mission; these savings have a present value of $3.1 B if the first Mars expedition starts 20 years from today. Such savings on a Mars exploration program beginning in 20 years would therefore economically justify Government spending of up to $3.1 B *today* if that investment results in halving the cost of space launch.

This estimate of the economic value of lower cost space launch does not include the benefit that such a lowering of cost would have to all other government payloads over the next 40 years, nor does it include any benefit it might have for the national economy.

We may also note that there is a significant discrepancy between the historical $420 K per kg cost of developing human-rated spacecraft and the approximately $55 K per kg cost of developing commercial aircraft over the same period. Because NASA's traditional program management methods are largely a function of organizational culture, it may be instructive to ask what might be the value of reducing the cost of developing human-rated spacecraft to two-thirds of previous levels. In that case, we can estimate the present value of the future savings at about $1.2 B today. Thus, it is economically worthwhile to invest up to $1.2 B in changing the manner in which NASA manages its programs, if that change will result in lowering future development costs to two-thirds of historical levels.

Cost Summary

A Mars Exploration Program starting in 2014, launching a first mission in 2024 and a mission every 26 months thereafter through 2044, is estimated to have a total cost of no more than $129 B over that period, or about $4.3 B per year.

Development of a nuclear thermal rocket has the potential to save $7.9-10 B if space launch costs remain at current levels. Lowering space launch costs to 50% of current levels would save $20-25 B. Reducing the cost of NASA human-rated spacecraft development to two-thirds of historical levels could save an additional $19.3 B.

Policy Implications and Recommendations for Shuttle Retirement

We assume that the Shuttle Orbiter will return to flight in 2005, as NASA has indicated. However, regardless of the safety measures incorporated, it will remain inherently deficient in its capability to provide the crew with an escape option in the event of a catastrophic failure at some point in the mission. Such a failure is inevitable if the Shuttle continues to fly indefinitely; we therefore agree with the Administration's decision to retire the vehicle in the 2010-2011 time frame.

Indeed, some have advocated that the Shuttle be retired now. We do not advocate this view; we believe that the Orbiter will be adequately safe to fly more missions into space, although its retirement should be accomplished as soon as practicable, given that it will have seen 25 years of use. We believe it is reasonable to fly again to complete construction of the ISS, at least to the "U.S. Core Complete" stage, which should be reached after only six to eight additional Orbiter missions and about two years. It appears, however, that to reach "Assembly Complete," with the international modules (JEM and Columbus) and perhaps the U.S. Habitation module in place, will take more than 20 additional flights and an additional four or five years. This appears to be stretching the program too far and, perhaps equally important, extending funding for the Shuttle Orbiter too far into the next decade, limiting funds available to move into succeeding Stages of the Exploration Initiative. There seems to be some official ambiguity on this point. NASA has indicated that the Orbiter will be retired in 2010, though this is likely to be well before "Assembly Complete" and would once again place the United States with no capability to reach LEO or the ISS, presumably necessitating reliance on the Russian Soyuz once again.

We propose instead that NASA plan to use the Orbiter only to "U.S. Core Complete" and plan to deliver the other heavy modules to the ISS with other launch vehicles, provided that agreement on this point can be reached with the international partners. Launch options are described in section 4, above. In this way, larger and international crews can begin to utilize the ISS even earlier than in the current planning. Also essential to this plan is the early development of a simple and robust CEV, designed to transport four to six crewmembers to and from LEO , and to remain with the crews during their stays at the ISS. When this is done, which should be before 2010, then the Orbiter can be retired and human access to space for the United States will not suffer another painful hiatus. The CEV design for this first stage might be identical externally to the more capable versions adapted for interplanetary travel in a later Stage of Exploration. It can be simpler, less massive, and cheaper to develop at this early phase because it will not be required to spend long manned periods in space, travel to distant destinations, or survive reentry at hyperbolic speeds.

Overview, Significant Issues, and Recommended Studies

We have described a three-stage plan for Moon/Mars Exploration. Stage 1 firmly establishes our Earth orbital capabilities with a new CEV capable of carrying four to six persons to and from LEO, including the ISS, before 2010. It requires the concurrent qualification of an appropriate launch vehicle, which we have suggested could be based on a single SRM augmented with a new lox-hydrogen upper stage (Fig. 1). With this system in place, and with the concurrence of the international partners, the Shuttle Orbiter can be retired at any stage of ISS assembly following "U.S. Core Complete."

In Stage 2 of the Exploration program, destinations at the Moon, NEOs, the Lagrange points, and the vicinity of Mars, including the Martian moons Deimos and Phobos, become possible. Each of these locations offers the potential of fascinating scientific return and broad public interest, while remaining within reasonable fiscal bounds. Finally, in Stage 3, human landings on the Moon and Mars are achieved.

Before the internal steps along the route through these three Stages can be fully defined, a number of confirming or defining studies must be completed.

- We have suggested that the earliest version (e.g., "Block 1") of the CEV be a simple design capable of carrying a crew of four to six to and from LEO. It would not be intended for long periods of independent free-flight or trips beyond LEO but would provide U.S access to LEO and the ISS and allow the Shuttle Orbiter to be retired. The CEV Block 1 design would allow the ISS be used by the United States both to qualify more and larger crews for later interplanetary travel and to assure mission planners that the internal dynamics of crew selection and skill provision were appropriate for long duration missions. It would also allow our international partners to begin their long-delayed research in the U.S. Lab and other existing facilities at the earliest possible time. It is expected that this Block 1 design could be available for testing by 2008 and manned by 2010. The question of the proper design configuration remains, and is important, because successive versions will be unlikely to (and should not) alter the vehicle's basic mould lines.

- The mass of the Block 1 CEV should be in the 13-15 metric ton range, including the abort system. We have suggested that the most suitable launch vehicle for the LEO CEV could consist of a single SRM, with a new lox-hydrogen upper stage. Candidate upper stage engines could include the Apollo-era J-2S or the SSME (likely modified for cheaper production if it is to be expended upon each use). Heavy-lift versions of Delta IV and Atlas V have been mentioned frequently as candidates for a CEV launcher and have ample payload capacity for the task, though considerable work may be required to human-rate them. Some study should be devoted to determining which option is best suited to early use; what choices would be the most cost-effective, safest, and most reliable; and what additional infrastructure would be required for each option.

- It would seem sensible to consider using various international launch vehicles at sites other than KSC—particularly Kourou, befitting its advantageous location—for launching both the CEV and other exploration hardware. Whether this is politically viable or practically implementable remains to be determined, but it should be studied.

- It will be necessary to upgrade the CEV to a "Block 2" version for missions beyond LEO. The Block 2 version will have requirements yet to be determined, but at a minimum it must be capable of long-duration interplanetary cruise missions to any of the destinations listed for Stage 2 or 3 exploration, presumably in combination with other modules (e.g., Hab, Lab, Consumables, Propulsion), which must be attached to [2]the CEV before departure on interplanetary trips. We are confident that a CEV "growth strategy" along these lines will allow an exploration version of the vehicle to be developed at the least possible incremental cost.

- NASA must define the fleet of U.S. launch vehicles desired to support human exploration beyond LEO.

- We have assumed that, at least initially, the assembly node for the collected modules will be in low-inclination LEO, and we have pointed out some of the penalties associated with the use of higher-inclination orbits. We have addressed some of the advantages of high-altitude assembly nodes but have not considered them likely candidates for early use. These issues should be addressed in more detail.

References

1. Morring, Jr., Frank, “Off the Ground,” Aviation Week and Space Technology, 28 June, 2004, p. 26.

2. "The Next Steps in Exploring Deep Space," a cosmic study by the International Academy of Astronautics, Review Draft 23 March 2004 http://www.iaanet.org/commissions/presentation.pdf

3. http://www.esa.int/SPECIALS/Aurora/ESA9LZPV16D_0.html

4. “Putin Acknowledges Budget Problems in Space Exploration,” Moscow, ITAR_TASS in English, 1730 GMT, 12 April 2004.

5. Murray, Charles, and Cox, Catherine Bly, “Apollo: The Race to the Moon.” (1989), pp. 100-102.

6. Setlow, R.B., “Mitigating Hazards of Space Travel,” Space News, 15 Mar 04, p. 13.

7. President’s FY 2005 NASA Budget Request: http://www.nasa.gov/pdf/55385main_01%20Front%20page%20Total%20Summary%20Table.pdf

8. Planetary Society Workshop: Stepping into the Future, a Workshop in Memory of the Columbia 7, April 29-30, 2003. http://planetary.org/workshop/index.html

9. Morring, Jr., Frank, “Space Nuclear Power,” Aviation Week & Space Technology, Vol. 60, No. 22, May 31, 2004, p. 66.

10. http://www.alfanaes.freeserve.co.uk/Session981.htm

11. Dewar, James A., To the End of the Solar System—The Story of the Nuclear Rocket, The University Press of Kentucky, Lexington, KY, 2004.