Use Of Russian Space Hardware In The Space Exploration Initiative

by

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ABSTRACT

The opportunity now exists to use Russian space hardware to help make the goals of the U.S. Space Exploration Initiative (SEI) achievable. The Russian space program has already developed many of the space assets needed for the SEI, and is willing to make them available at a price that is far less than what it would cost the U.S. to develop an equivalent capability. There are a number of problems, however, with the use of Russian space hardware in the SEI, including the possible harm that such use might cause to U.S. industry, the risk of relying on the unstable Russian space program, and national security concerns.

This paper attempts to determine whether the benefits of using Russian space hardware in the SEI would outweigh the costs. First, the SEI and the Russian space program are examined. The knowledge thus gained is then used to help determine the issues involved in the use of Russian space hardware in the SEI and the feasibility of various methods of carrying out such use. Next, the basic hardware requirements of the SEI are determined, and various items of Russian space hardware are examined against technical, economic, and policy-related criteria to see if they are superior to any alternative in meeting the requirements.

Finally, two schemes for the use of Russian hardware in the SEI are proposed: a low risk scenario with limited U.S./Russian interaction, and a higher risk approach that could result in greater benefits.

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My parents (despite their suggestion that I begin the thesis "It was a dark and stormy night on the windswept steppes of central Kazakhstan . . .")

The crew of the NHOWP, my home on the strange

All the people who anchor my bungee cord o' luv

The Socially Conscious Attack Engineers of TPP

The Zen Jihad

Absent friends, lost loves, dead gods, and the season of mists

Contents

I. Introduction

For thirty years, the United States and the Soviet Union battled for dominance in space. With global prestige at stake, the two superpowers initially poured money and resources into their space programs in an effort to beat each other to a series of goals: first satellite, first man in space, first man on the Moon. After the United States won the race to the Moon, the competition continued, but the directions of the Soviet and American space efforts diverged, due to differing goals, philosophies, and technical strengths. By the late 1980s, the two nations had developed extensive space programs with markedly different technical capabilities.

The revolutionary changes that swept the USSR and its offspring republics over the last few years have created an opportunity for the United States to use Russia's unique space capabilities to aid in achieving its own space goals.[1] Such a course of action would have been extremely difficult to realize as recently as the 1980s, but many of the barriers that then stood in the way have since been removed. National security concerns about working with Russia eased with the end of the Cold War and the dissolution of the USSR. Secrecy about most Russian space hardware has evolved into a fairly high degree of disclosure. Perhaps most importantly, diffident early attempts to market a few space services have grown into near-desperate efforts by both government leaders and space program managers to sell almost any item of Soviet space hardware.

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[1]Russia has authority over the overwhelming majority of the former Soviet Union's space assets.

One U.S. space effort in particular, the Space Exploration Initiative (SEI), has a great deal to gain by using Russian space hardware. The SEI is intended to be a long-duration sustained program of human exploration of the solar system, with the initial objectives of returning astronauts to the Moon and exploring Mars, but it is currently in serious jeopardy of being eliminated due to a combination of its high cost and a lack of congressional support for its goals. The use of Russian space hardware in the SEI could do much to alleviate both of these problems. First, the Soviet space program has already developed many of the space assets that the SEI requires to meet its goals, and is willing to make them available at a price that is far less than what it would cost the U.S. to develop an equivalent capability. Second, Russian participation in the SEI could give the initiative the impetus it needs to gain support from Congress and the public.

There are a number of problems, however, with the use of Russian space hardware in the SEI. One is that the situation within the former Soviet Union is still far from stable; it is not clear whether particular items of Russian hardware will continue to be manufactured, or deals made with Russian organizations will continue to be honored, over the long time frame of the SEI. Another problem is that the use of Russian space hardware in the SEI might harm the U.S. aerospace industry, not only by taking work away from U.S. firms, but also by strengthening potential Russian competition. A third set of problems have to do with national security issues; U.S. purchase of Russian space hardware might help maintain the Soviet military-industrial complex, and close cooperative endeavors might allow the Russians to acquire advanced U.S. technology.

It is clear, then, that there are both advantages and disadvantages to the use of Russian space hardware in the SEI. This paper attempts to determine, on a case-by-case basis, whether the benefits of using Russian space hardware in the SEI would outweigh the costs. The basic approach taken was to first determine the economic, policy, and technical issues involved in such an endeavor and then to measure the Russian hardware against the SEI's requirements, using the economic, policy, and technical issues as criteria.

Determining the technical feasibility of using an item of Russian space hardware in the SEI is relatively straightforward. Probable hardware requirements for SEI missions can be derived from the various strategies that have been proposed for carrying out the SEI; the performance characteristics (including the reliability) of the particular hardware can then be examined to determine whether it meets the SEI's requirements. Many items of hardware will require some modifications in order to meet the SEI's requirements; the feasibility and cost of performing any necessary modifications must be taken into account in the overall determination of the hardware's suitability for use in the SEI.

The economic and policy criteria used to determine if a given item of Russian space hardware should be used in the SEI do not, at first glance, seem to be significantly more complex than the technical criteria. The basic economic criterion is the overall cost of using the Russian space hardware, including any purchase price, the costs of integrating the hardware into the rest of the SEI, and the effects of the purchase on the U.S. aerospace industry. The fundamental policy criterion is the political feasibility of the use of Russian hardware, both within the U.S. and Russia, and in the international policy environment. Both the economic and policy implications of the use of Russian space hardware depend strongly on the methods by which the hardware would be acquired for use in the SEI. For example, the cost and political implications of using a Russian launch vehicle will be different if the vehicle is directly purchased by the U.S. than if the vehicle is launched by the Russians within the framework of a large-scale international cooperative program.

A number of factors, however, add complexity to both the economic and policy criteria. First, it is often difficult to assess even the present-day costs or political implications of a large-scale endeavor such as the incorporation of Russian hardware into the SEI. The costs of developing new hardware, for example, are notoriously difficult to determine; NASA has had difficulty in estimating the costs of its major programs to within even a factor of two. Second, neither the economic costs nor the political implications of the use of Russian space hardware are likely to remain constant over time. The Russian reaction to the U.S. purchase of a space station, for example, may be different in 1998 than it is in 1992--Russia may not exist as a separate republic in 1998!

Despite these difficulties, it is still possible to get a fairly good answer to the question of whether Russian space hardware should be used in the SEI. First, estimates of cost and political feasibility may not be entirely accurate, but a high level of accuracy is not necessary to determine which hardware items are clearly worth using and which ones obviously are not. Second, while it may not be possible to accurately predict the future of the SEI or the Russian space program, careful study of these institutions' pasts, and of the forces working to change them (rather than on the details of their present configuration), can at least lead to an idea of the range of future directions they might take, and to an understanding of ways in which their future might be shaped.

This paper first examines the SEI (Chapter II) and the current Russian space program (Chapter III) from an institutional perspective, focusing on the forces that are driving the evolution of the two programs. In Chapter IV, the context of international interactions in the SEI is examined and, drawing from the previous two chapters, a set of guidelines for handling the use of Russian hardware in the SEI is established. In Chapters V and VI, published SEI strategies and the basic principles of space travel are used to derive the hardware requirements for the SEI. In Chapter VII, various items of Russian space hardware are evaluated, using technical, economic, and policy criteria, to determine whether they should be used to meet these requirements. Finally, in Chapter VIII, recommendations for the use of Russian space hardware in the SEI are proposed.

II. The Space Exploration Initiative

The Space Exploration Initiative (SEI) is a NASA-led multi-agency effort to carry out a sustained program of extending human presence and activity beyond Earth orbit and into the Solar System. To fully understand the implications of the possible use of Russian space hardware within the SEI, it is necessary to first understand the initiative's history and its political and institutional standing.

History of the Space Exploration Initiative

The Creation of the SEI: 1984-1989

In the 1989 speech that was the go-ahead signal for the Space Exploration Initiative[2], George Bush said "...there's very little question that, in the 21st century, humans will again leave their home planet for voyages of discovery and exploration. What was once improbable is now inevitable." What was less inevitable and much more improbable was that the the already overcommitted U.S. space program was, with the support of the Administration, preparing to launch into an ambitious open-ended program of human exploration of the Solar System. This improbable occurrence can be traced to the conjunction of such disparate elements as a twenty year old vision for the future of the space program, a perceived need for long-term national goals in space, the re-evaluation of the space program after the Challenger accident, attempts to rally support for the space station program, and a reorganization of the nation's space policy making process.

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[2]George Bush, "Remarks on the 20th Anniversary of the Apollo 11 Moon Landing", July 20, 1989.

Figure II-1 diagrams the major motives and actions that eventually resulted in the creation of the SEI. The figure is chronological, covering (from top to bottom) the period from 1984 to 1989.

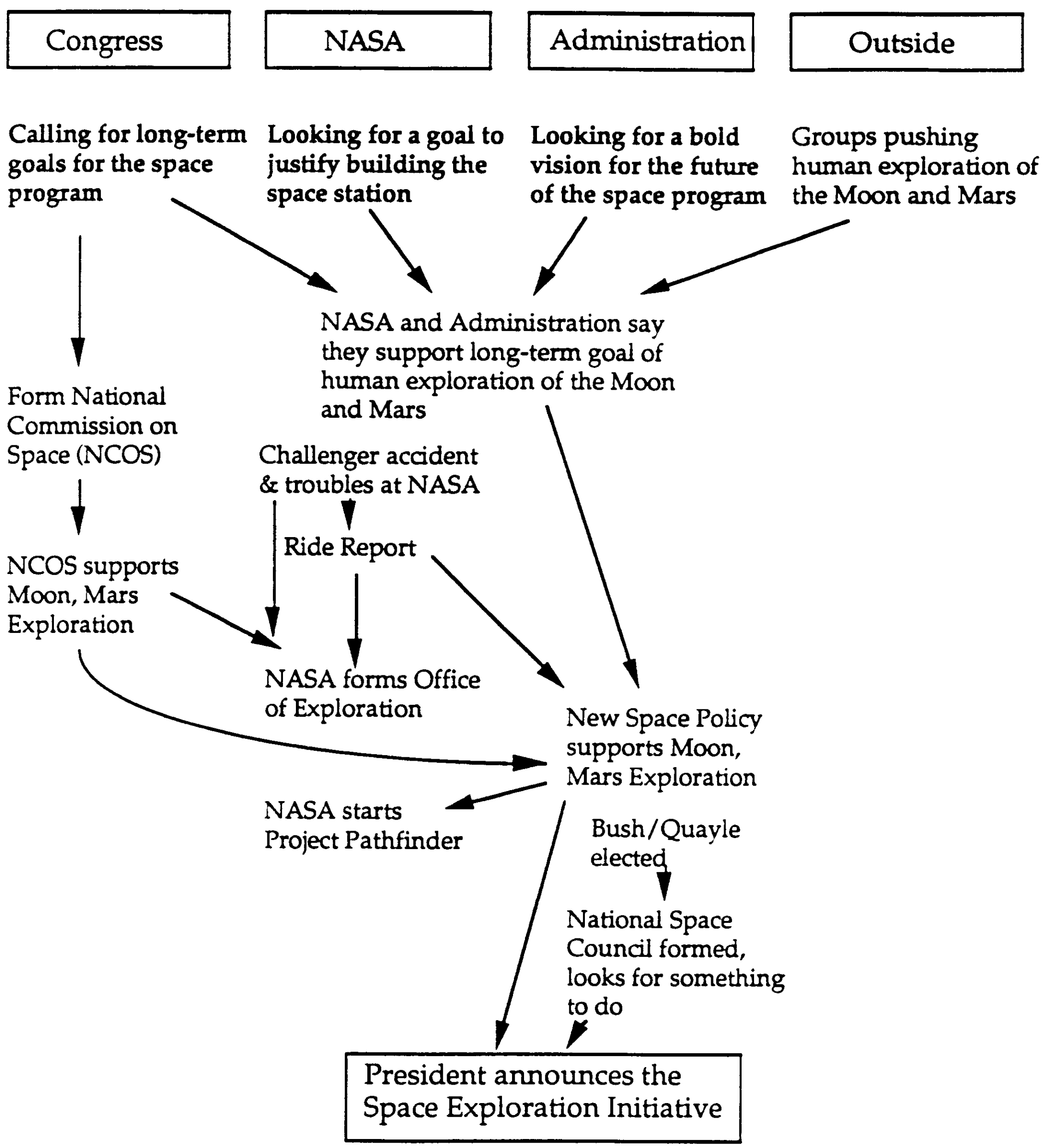

Figure II-1: Creation of the SEI 1984 - 1989

Although the SEI as it currently exists only began to pick up momentum in the early 1980s, previous efforts to mount such an endeavor had taken place as far back as the Nixon Administration. In 1969, Nixon's Space Task Group recommended that the United States adopt a long-range goal of manned planetary exploration, with the first target a manned Mars mission before the end of the century.[3] President Nixon endorsed this goal in 1970, but public and political reaction was decidedly negative and support from the White House soon disintegrated.[4] Lukewarm support for the space program through the 1970s led NASA to concentrate its resources on the space shuttle, and put Moon and Mars exploration plans on hold. President Carter's Space Policy specifically stated that "It is neither feasible nor necessary at this time to commit the United States to a high-challenge space engineering initiative comparable to Apollo."[5]

Hopes for further human space exploration efforts remained dim in the early 1980s. No support for such activity was evident from the Reagan Administration, and advocacy within NASA was also muted, as exploration did not fall under the clear jurisdiction of any Associate Administrator. President Reagan's 1984 endorsement of the space station appeared to further lower the chances for any near-term human exploration effort, as it seemed clear that the proposed space station would absorb much of NASA's resources

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[3]Michael A. G. Michaud, "Let's go to Mars - With Out Friends and Allies", The Case for Mars III: Strategies for Exploration - General Interest and Overview, San Diego: Univelt Inc., 1989, p.109.
[4]Leonard David, "Political Acceptability of Mars Exploration: Post-1981 Observations, The Case for Mars II, San Diego: Univelt Inc., 1985.
[5]"U.S. Civil Space Policy", White House Fact Sheet, Office of the White House Secretary, October 11, 1978.

and energy for at least a decade, and it was hard to imagine Congress and the Administration initiating an additional large space project during that time.[6]

Groups both within and outside NASA, however, were studying and promoting a return to the Moon and expeditions to Mars. Notable among these groups were the "Mars Underground" and the Lunar Base Working Group, which held conferences discussing the technical, political, and economic aspects of further exploration of the Moon and Mars.[7,8,9,10] A concurrent endeavor, which received a great deal of publicity, was an effort by opponents of the U.S. Strategic Defense Initiative to promote a joint U.S.-Soviet mission to Mars. Advocates of this mission, who saw it as an alternative to military competition between the U.S. and the USSR in space, included Senator Spark Matsunaga and the leadership of the Planetary Society, a prominent space science-oriented group.[11]

At the same time the visibility of human space exploration was rising, the consensus was growing that the nation's space program would be improved if long-term goals were adopted and used to determine what kind of hardware should be built.[12] This call to define the nation's long-term goals in space was issued in the middle of a heated battle over the development of the space station while, in the background, various groups were promoting

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[6]John Logsdon, "Dreams and Realities: The Future in Space", Lunar Bases and Space Activities of the 21st Century, Houston: Lunar and Planetary Institute, 1985, p.707.
[7]W.W. Mendell, ed., Lunar Bases and Space Activities of the 21st Century, Houston: Lunar and Planetary Institute, 1985.
[8]Penelope J. Boston, ed., The Case for Mars, San Diego: Univelt Inc., 1984.
[9]Christopher P. McKay, ed., The Case for Mars II, San Diego: Univelt Inc., 1985.
[10]Carol Stoker, ed., The Case for Mars III: Strategies for Exploration - General Interest and Overview, San Diego: Univelt Inc., 1989.
[11]Michael A. G. Michaud, "Let's go to Mars - With Out Friends and Allies", The Case for Mars III: Strategies for Exploration - General Interest and Overview, San Diego: Univelt Inc., 1989, p.111.
[12]Office of Technology Assessment, Civilian Space Stations Assessment, Washington: U.S. Government Printing Office, 1984, p.126.

human space exploration. The end result was that space station advocates began to claim that the space station was just the first step towards reaching a long-term goal of human space exploration. This connection was emphasized by the Reagan White House Science Advisor, George Keyworth, who said in June 1984 "...the President announced the space station initiative - not as an end in and of itself, but as a first step toward many new exciting long-term goals in space. A manned space station will be, first and foremost, a doorway to exploring and developing the solar system."[13]

At this point, official talk of future exploration endeavors was quite clearly nothing but rhetoric, but the concept had now been aired in public and endorsed by both NASA and the Reagan Administration. In the mid- to late-1980s, a sequence of events further raised the profile of human space exploration and began to pressure NASA into making the exploration effort more than just a nebulous justification for the construction of the space station. The first of these events was the study and report of the National Commission on Space (NCOS).

Congress, still trying to define long-term goals for the space program, created the NCOS and charged it with formulating a "bold agenda to carry America's civil space enterprise into the 21st century." The NCOS was composed of fifteen members both from outside and within the space field and was chaired by Thomas O. Paine, a former NASA Administrator. Its report, Pioneering the Space Frontier,[14] which was published in 1986, proposed a national mission for 21st-century America of "lead[ing] the exploration and development of the space frontier, advancing science,

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[13]Leonard David, "Political Acceptability of Mars Exploration: Post-1981 Observations", The Case for Mars II, San Diego: Univelt Inc., 1985, p.43.
[14]National Commission on Space, Pioneering the Space Frontier, Bantam Books, 1986.

technology and enterprise, and building institutions and systems that make accessible vast new resources and support human settlements beyond Earth orbit, from the highlands of the Moon to the plains of Mars." As Paine was the same man who had recommended exploration of the Moon and Mars to the Nixon Administration, it was perhaps no surprise that the NCOS recommended the robotic and human exploration of the Moon and Mars.

The Challenger accident in early 1986 overshadowed the publication of the NCOS report, but it also encouraged further review of the space program and led to the real possibility of major changes in the space agency. The string of setbacks that plagued NASA over the next few years, including the lengthy shuttle stand-down, rising cost estimates for the space station, and the problems of the Hubble Space Telescope, kept reviews of the agency coming and also maintained the pressure on NASA to heed the recommendations made in the reviews.

One important review began in 1987, when the NASA Administrator formed a task group "in response to growing concern over the posture and long-term direction of the U.S. civilian space program" to "define potential U.S. space initiatives, and to evaluate them in light of the current space program and the nation's desire to regain and retain space leadership."[15] The NASA task group attempted to find a set of goals that would be consistent with both the national interest and NASA's capabilities. The group's report (known as the "Ride report" after its main author, astronaut Sally Ride) recommended four possible initiatives for further study and evaluation. These were 1) Mission to Planet Earth, 2) Exploration of the Solar System, 3) Outpost on the Moon, and 4) Humans to Mars. One sign of NASA's post-

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[15]Sally K. Ride, Leadership and America's Future in Space, Report to the NASA Administrator, August 1987, p.7.

Challenger willingness to respond to recommendations came when, as recommended in an early draft of the Ride report, the NASA Administrator established the Office of Exploration to fund, direct, and coordinate studies related to human exploration "in response to an urgent national need for a long-term goal to energize the U.S. civilian space program and stimulate the development of new technology."[16]

Events high in the executive branch then began to propel human space exploration towards a prominent place in the space program. The first of these was a Senior Interagency Group on Space[17] review of national space policy. This review, which was prompted by the Challenger accident, growing foreign space capabilities, and the perception of a "space leadership crisis,"[18] drew from the NCOS and Ride reports, and resulted in a new national space policy, which was approved by President Reagan on January 5, 1988. Official support for human space exploration, at least as an eventual goal, was manifested in the policy's list of six overall goals of U.S. space activities, of which the only new one was: "as a long-range goal, expand human presence and activity beyond earth orbit into the solar system." As a part of the long-range goal to expand human presence and activity beyond Earth orbit, NASA was directed to pursue the "Pathfinder" program, a systematic development of technologies to enable and support a range of future human space exploration missions.[19]

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[16]Office of Exploration, NASA, Beyond Earth's Boundaries, 1988 Annual Report to the Administrator, 1988, p.7.

[17]SIG-Space included representatives from the Departments of State, Defense, and Commerce, NASA, the OMB, the Joint Chiefs of Staff, and the CIA, and was chaired by a member of the National Security Council

[18]Roger DeKok, "National Space Policy" Presentation to the NAS/NAE Committee on Space Policy, June 16, 1988.

[19]Patricia E. Humphlett, Civilian Space Policy Under the Reagan Administration: Potential Impact of the January 1988 Directive, Congressional Research Service, March 21, 1988.

The election of George Bush gave further momentum to the push for an exploration initiative. While still vice-president, Bush had voiced support for human space exploration, saying "We should make a long-term commitment to manned and unmanned exploration of the solar system. There is much to be done --further exploration of the Moon, a mission to Mars, probes of the outer planets. These are worthwhile objectives, and they should not be neglected."[20] Very early in his Administration, Bush created a National Space Council (NSC) to coordinate national space policy, a move that was instrumental in furthering the cause of a human space exploration initiative.[21]

The National Space Council replaced the space policy mechanism used during the Reagan Administration, in which SIG-Space recommended space policy and transmitted its recommendations to the president through the National Security Council. The National Space Council is a much higher profile body than SIG-Space used to be; it is chaired by the Vice President and its members include the NASA Administrator, the Secretaries of State, Treasury, Defense, Commerce, and Transportation, the Directors of the Central Intelligence Agency and the Office of Management and Budget, the President's Chief of Staff, and the Assistants for National Security Affairs and for Science and Technology. The formation of the National Space Council increased the prominence of space in the Administration and of civilian space efforts within the overall national space program. Importantly, it also presented the Vice President with an opportunity to show leadership.

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[20]George Bush, "Space", Speech at Huntsville AL, October 20, 1987.
[21]George Bush, "Message to the Congress Transmitting a Report on the Establishment of the National Space Council", February 1, 1989.

In the spring of 1989, the Vice President took that opportunity and met with NASA officials to discuss future plans for the space program.[22] Considering the prominence that human space exploration had achieved by this time, it is not surprising that it was chosen to be the Administration's new space initiative. The decision was announced by President Bush on the 20th anniversary of the Apollo 11 Moon landing. In his speech, he called for "a national commitment to a sustained program of manned exploration of the solar system and the permanent settlement of space". His proposal in the speech was for "a long-range continuing commitment," beginning in the 1990s with the space station, followed by a return to the Moon, "this time to stay", and finally a manned mission to Mars, "with each mission laying groundwork for the next." The President then called upon the Space Council to come up with "concrete recommendations to chart a new and continuing course to the Moon and Mars and beyond."[23]

Defining the SEI: 1989-1992

The period between the president's call for a program of human space exploration and the present has been marked by two major conflicts over the future of the SEI. These battles began shortly after the President's announcement and have only recently begun to cool down. One of the battles was fought between the Bush Administration and NASA over the relative importance of the SEI and the space station program. The other, over the size of the SEI and the speed with which it should start, was fought

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[22]Franklin Martin, "Human Exploration Initiatives: Mission Concepts", in Leaving the Cradle: Human Exploration of Space in the 21st Century, 28th Goddard Memorial Symposium, San Diego: Univelt Inc., 1991.
[23]George Bush, "Remarks on the 20th Anniversary of the Apollo 11 Moon Landing", July 20, 1989.

between the Administration and Congress. Complicating the situation, these two battles occasionally spilled over into each other and the institutions involved did not always act monolithically. Figure II-2 diagrams the major motives and actions that influenced the development of the SEI over the period from 1989 to 1992 .

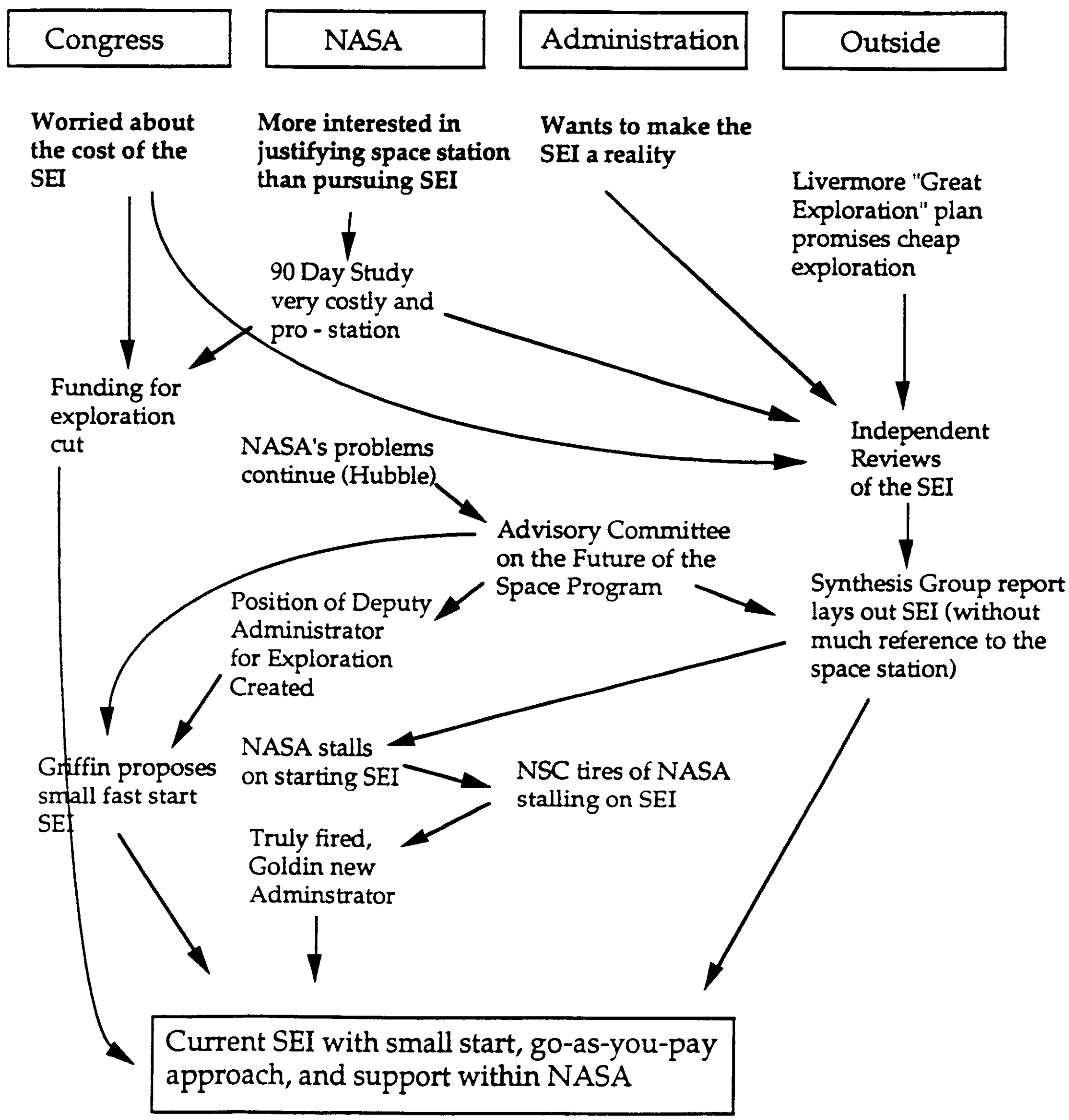

Figure II-2: Defining the SEI 1989 - 1992

The battle between the Bush Administration and NASA over the relative importance of the SEI and the space station only really began after the SEI was endorsed by Bush. Before this event, NASA had been mildly supportive of efforts to promote human space exploration, as such endeavors had helped provide a justification for the space station project. When told to, the Agency had initiated the Exploration Office and "Project Pathfinder", but it had not invested a lot of energy in either of them. As human exploration did not have any strong advocates in the Reagan Administration, NASA did not get into trouble for this policy of lukewarm support for human exploration of the solar system.

The situation changed after Bush's 1989 endorsement of human space exploration as a major national goal. Suddenly, the SEI had been elevated to a serious potential competition to the space station. This status galvanized opposition to the SEI within NASA, as the space station was the agency's largest development project.[24] The SEI represented a particularly dangerous threat to the space station because it seemed likely that if the Administration was forced to choose to keep one major space initiative, it would choose "its own" program rather than the space station, which was a legacy of the Reagan Administration.

While the SEI did have supporters within NASA, the Office of Exploration (which did not have its own Associate Administrator) was no match for the powerful Office of Space Station. The result was that NASA was inclined to try to shape the SEI so that it would support the space station, or at least not compete with it. Because of the SEI's high profile, however,

[24]It seems possible that years of defending the space station from Congress had ingrained NASA management with the habit of defending the station against any possible threat; this might be a contributing cause to the Agency's reaction.

NASA's actions along these lines could not go unnoticed. This resulted in considerable conflict with the Bush Administration, which was interested in seeing the SEI succeed, even if its success might cause trouble for the space station program.

The other big battle over the SEI during this time period was the conflict between the Bush Administration and Congress over the initiative's size and the speed with which it should start. Though Congress had supported the search for long-term space goals, few members were willing to pay for a major new space development program while the space station was still being built. The Congressional Budget Office had estimated that the plans put forth by the National Commission on Space and the Ride Report would require an annual NASA budget in excess of $20 billion/yr by the mid-1990's and over $30 billion/yr by 2000,[25] and most in Congress were unwilling to increase NASA's budget to those levels.

A number of other factors added to Congress' resistance to funding the SEI. First, many in Congress had developed a distrust of the space agency's cost estimates during the lengthy battles over the space shuttle and space station programs. In a similar vein, many were wary of NASA's propensity for using a "funding wedge" (in which funding requirements for apparently small programs are increased each year) to get major projects started. Third, supporters of the space station program in Congress shared NASA's apprehension about the possibility that the SEI might supplant the space station. Finally, some in Congress supported a third major project, the environment-monitoring Earth Observing System, over both the space

[25]Congressional Budget Office, The NASA Program in the 1990s and Beyond, May 1988, p.51.

station and the SEI. The combination of all these factors provided formidable obstacles to the Bush Administration's attempts to get the SEI started.

The event that marked the real beginning of both of these battles was the publishing of NASA's "90-Day Study" on the SEI.[26] (NASA had carried out this study to support the Space Council in its task of coming up with "concrete recommendations for the SEI.") The report was notable for its emphasis on the space station (mentioned 18 times in the executive summary, for example) and its estimate (deleted before publication) that the cost of the 30-year initiative would exceed $400 billion.[27] Cynical observers said the 90-Day report was recycled from post-Apollo plans made twenty years ago, with the phrase "Space Station Freedom" inserted wherever possible.[28] Adding fuel to the fire, a group of scientists at the Department of Energy's Lawrence Livermore Laboratory asserted that the NASA "three decades and $400 billion" lunar and Mars program was untenable,[29] and proposed their own ambitious plan ("The Great Exploration") to put humans on Mars within 10 years for less than $10 billion.

Shock at the vast price tag on NASA's plan and at the low cost of the Livermore proposal led the National Space Council to call for a nationwide search for new ideas and innovative technologies to "ensure all reasonable space exploration alternatives have been evaluated."[30] NASA proposed awarding six to ten $1 million study contracts to industry to perform this

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[26]NASA, Report of the 90-Day Study on Human Exploration of the Moon and Mars, November 1989.
[27]James R. Asker, "NASA Offers Five Alternatives For Landing Humans on Mars by 2018", Aviation Week and Space Technology, November 27, 1989.
[28]James Vedda, "Relearn Moon Before Trying Mars", Space News, September 17-23, 1990.
[29]Andrew Lawler, "Livermore Group Proposes Cheap Mission to Mars", Space News, November 13, 1989.
[30]NASA, "NASA's Space Exploration Package", Thomas O. Paine, ed., Leaving the Cradle: Human Exploration of Space in the 21st Century, 28th Goddard Memorial Symposium, San Diego: Univelt Inc., 1991, p.87.

nationwide search,[31] but Congress instead mandated the creation of a three-part outreach program to gather ideas on the SEI from a wide variety of sources. The first part of this program was a campaign to gather ideas from industry, universities, federal laboratories, and the general public. The second was an effort to gather ideas from the technology-related agencies, and the third was a technology assessment led by the American Institute of Aeronautics and Astronautics. These ideas were then to be reviewed by a group of outside advisors known as the "Synthesis Group," who would recommend program architectures and pertinent technical opportunities to NASA.

While the outreach program was underway, President Bush continued to push the SEI forward. First, he announced a new policy that further defined the SEI in March, 1990.[32] The new policy placed emphasis on broad early technology development and the definition of possible schemes for human space exploration. It also named NASA as the principal implementing agency for the SEI, and gave the Departments of Energy and Defense major roles in technology development and concept definition. The National Space Council was tasked with developing an implementation strategy for the initiative. Later that spring, the President gave the initiative another push, saying that "before Apollo celebrates the 50th anniversary of its landing on the Moon [2019] the American flag should be planted on Mars."[33]

Congressional support for the exploration initiative, however remained low --Senator Gore proclaimed that the Administration needed a

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[31]Douglas Isbell, "Congress says OK to Moon, Mars Work", Space News, May 28 - June 3, 1990.
[32]The White House, "Statement by Press Secretary Fitzwater on the President's Space Exploration Initiative", March 8, 1990.
[33]George Bush, "Remarks at the Texas A&I University Commencement Ceremony in Kingsville, Texas", May 18, 1990.

"mission to reality"[34] if it thought the SEI was going to be funded. Congress showed its lack of support for the exploration initiative as defined by President Bush by deleting almost all of the President's exploration funding request for 1991, over the Administration's strong protests. NASA, more concerned with getting funding for the space station, reportedly did not lobby very hard to keep the funding.[35, 36]

This defeat for the SEI, and the publishing of the report of the Advisory Committee on the Future of the U.S. Space Program[37] in December of 1990 led to a reassessment of the funding strategy for the initiative, and a strengthening of the SEI's position within NASA. This Advisory Committee had been chartered by NASA and the Vice President as a response to concerns about the state of NASA's programs and institutions, and was charged with advising the NASA Administrator on overall approaches that NASA management could use to implement the civil space program.

One of the report's important recommendations was that the SEI should adopt a "go-as-you-pay" funding approach, meaning that the initiative

> "should be programmed to proceed at a schedule consistent with available funding and the establishment of a solid technology underpinning. When there are problems in the program, as there will always be, the schedule should be slipped rather than taking money from other programs such as the research program."[38]

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[34]Douglas Isbell and Andrew Lawler, "Senators Assail Bush Plan", Space News, May 7-13, 1990.

[35]Andrew Lawler, "Bush Moon-Mars Plan Handed First Defeat", Space News, June 18-24, 1990.

[36]Andrew Lawler, "Moon, Mars Fight Escalates", Space News, June 25-July 1, 1990.

[37]Advisory Committee on the Future of the U.S. Space Program, Report of the Advisory Committee on the Future of the U.S. Space Program, U.S. Government Printing Office, 1990.

[38]Synthesis Group on America's Space Exploration Initiative, America at the Threshold: America's Space Exploration Initiative, U.S. Government Printing Office, Washington, 1991, p. 17.

The Administration, stung by its failure to get funding from Congress for an aggressive Moon-Mars program, adopted the go-as-you-pay approach for the SEI in 1991, and played down the exploration role for its advanced technology programs.[39] This was a significant turnaround from the "Mars by 2019" goal, but it succeeded in getting Congress to increase funding for exploration-related work for 1992.

The report of the Advisory Committee also had a major effect on the ongoing struggle over SEI between the Bush Administration and NASA. First, the report said that the space station was not needed as a transportation node for exploration. The Committee instead saw the main role for the space station as being a platform for "life sciences experimentation and the development and verification of long duration space operating systems."[40] The long-awaited output of the Outreach Program, the report of the Synthesis Group on America's Space Exploration Initiative, seconded this observation, but went even further, questioning the ability of NASA's space station to even provide life science data.[41]

Another of the Advisory Committee's recommendations was that NASA establish the position of Associate Administrator for Exploration; this Associate Administrator would have the responsibility of planning, overseeing, and integrating technology bases and program elements related to both manned and unmanned exploration missions.[42] This recommendation

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[39]Andrew Lawler, "Bush Shifts Strategy on Moon, Mars Proposals", Space News, April 15-21, 1991.

[40]Advisory Committee on the Future of the U.S. Space Program, Report of the Advisory Committee on the Future of the U.S. Space Program, U.S. Government Printing Office, December 1990, p. 29.

[41]The Synthesis Group was composed of 27 space experts, many with experience in the Apollo program, and was chaired by former astronaut General Thomas Stafford, p.102.

[42]Advisory Committee on the Future of the U.S. Space Program, Report of the Advisory Committee on the Future of the U.S. Space Program, U.S. Government Printing Office, 1990, p.28.

was also seconded in the Synthesis Group report, which, in addition, recommended that NASA establish a long-range strategic plan with the SEI as its centerpiece.[43]

To the NASA leadership, the cumulative effect of these recommendations was to greatly increase the SEI's potential threat to the space station. First, the SEI was no longer a plausible justification for building the space station; it could even conceivably result in the station being redesigned or cancelled. Second, the appointment of an Associate Administrator would strengthen the SEI relative to the space station. Finally, if NASA were to establish a long-range strategic plan with the SEI as its centerpiece, the balance would be tipped even further towards the SEI.

NASA, after a lengthy delay, eventually appointed an Associate Administrator for Exploration in August 1991.[44] Despite a general lack of support from the top of the Agency, the new Associate Administrator moved quickly, proposing simple early robotic missions to the Moon, and experiments with innovative procurement methods.[45] The exploration funding request for 1992, however, was still reduced, as the NASA leadership accepted an overall funding cut for the agency in exchange for saving the space station.

In early 1992, the Bush Administration made a series of moves that effectively ended the battle with NASA over the SEI. The first came in February, when Bush demanded the resignation of NASA Administrator Richard Truly. Truly's continued support of the space station at the expense

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[43] Synthesis Group on America's Space Exploration Initiative, America at the Threshold: America's Space Exploration Initiative, U.S. Government Printing Office, Washington, 1991.
[44] Andrew Lawler, "NASA Names Chief for Exploration", Space News, August 26-September 8, 1991.
[45] Andrew Lawler and Debra Polsky, "Griffin: Start Small on Exploration Project", Space News, November 18-24, 1991.

of the SEI and the rest of the space program is thought to have been one of the major causes behind his ouster. As an administration official put it, Truly "was not a team player with the programs the White House was pushing."[46] The second move was the release of a new national space policy directive dealing with SEI strategy.[47] This policy formalized the SEI's status as a multi-agency organization led by the Associate Administrator for Exploration, and codified most of the Synthesis Group's organizational recommendations. Bush's final move that spring was the appointment in April of Daniel Goldin, an "outsider" with no strong connections to existing NASA programs, as the new NASA Administrator.[48]

The Future of the SEI

The SEI has come a long way since the mid-1980's. It is now established in NASA, with an Associate Administrator to give it bureaucratic standing and prestige. Major reviews of the space program have been positive about the value of a major exploration initiative, and the President and Vice President have voiced strong support for the SEI. Despite this, the SEI remains in a precarious situation and will have to struggle for funding, and perhaps for its very existence, for the foreseeable future. The future of the SEI will depend primarily on its support from the President and Congress, though the public, NASA, the Department of Defense (DoD), the Department of Energy (DoE), and the aerospace industry may also play a role. The ways in

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[46]Andrew Lawler, "Truly Ouster Was Two Months in the Making", Space News, February 17-23, 1992.
[47]George Bush, Space Exploration Initiative Strategy, National Space Policy Directive 6, March 9, 1992.
[48]Andrew Lawler, "TRW's Goldin is Surprise Pick to Head NASA", Space News, March 16-22, 1992.

which each of these groups can influence the future of the SEI are outlined below.

The Presidency

The fate of the SEI is highly dependent on support from the President. Without the continued support of the Bush Administration, the SEI would probably cease to exist. There is no sign that the Bush Administration is slackening in its support of the SEI, though; if re-elected, Bush and Quayle seem very likely to continue trying to expand the SEI. If Bush is defeated in the 1992 election, though, the SEI would almost certainly be eliminated as Senator Gore, a long-time foe of the SEI, would become the head of the NSC.

Even if Bush is re-elected and supports the SEI for the next four years, the initiative will still probably be far from secure. The SEI is inherently a long-term plan; in the SEI architectures proposed by the Synthesis Group, no missions are launched until 1998. It seems unlikely that four more years of support will make the SEI strong enough to survive opposition from a President; Executive Office support will probably be required through 2000 for the initiative to survive. (Of course, considering the long time frame of the SEI, the program might be able to rise again after a four-year cancellation.)

Congress

Though the President may determine if the SEI will survive or be cancelled, Congress will largely determine if it will ever grow to be more than a small research program. The significant budget increases required to begin major work on the SEI seem very unlikely to be approved in the current constrained budget climate. Barring some major event it seems unlikely that significant funding for the SEI will become available before the turn of the century, when space station costs should begin to decline. One major event that could result in early significant funding for the SEI would be cancellation of the space station program. Others might be the the rise of a strong lobby for the SEI, or even the development of a convincing rationale for pursuing the initiative.

Though it is unwilling to make a major commitment to the SEI, Congress may be more willing to fund small SEI-related programs than it has been in the past. There are a number of reasons why this may be so. First, Congress may be more willing to trust NASA's cost estimates and future plans now that "outsiders" are running both the Agency and the SEI. Second, the SEI has followed most of the recommendations made about it by the various advisory groups --it seems unlikely that it will become a money sink like the shuttle and space station programs. Third, NASA is more likely now to lobby hard to support SEI funding.

The Public

One reason that Congress has not been very supportive of the SEI may be that there is little public support for missions to the Moon and Mars. A February 1992 survey[49] found 49% of Americans supporting a permanent lunar settlement and 60% supporting a human mission to Mars. Enthusiasm was higher for new launch systems (67%), the space station (68%), the national aerospace plane (70%), joint space missions with other countries (77%), and satellites to monitor the environment (91%). In general, public enthusiasm for space projects drops rapidly when they are asked to choose between space projects and other programs (i.e. building a space

[49] Andrew Lawler, "Poll Shows Americans Like Earth Observation", Space News, March 23-29, 1992.

station vs. building affordable housing), so real support may be lower than these figures would indicate.[50]

This low public support for the SEI could result in the termination of the program; in any case it seems likely to weigh against its expansion. Public support for the SEI is unlikely to change drastically unless a better rationale for pursuing the initiative is developed. Some rationales that might influence public opinion could be the development of space resources (perhaps touted as a benefit to Earth's environment), or the use of the SEI as a symbol of international cooperation.

NASA

Support within NASA can, as we have seen, have an effect on a program such as the SEI. The battle between the station supporters and SEI supporters, however, has already swung towards the SEI; this support seems likely to increase as time goes on. NASA still has a lot riding on the space station project, but it in the next few years the project will probably either be built or killed. Either result will leave the SEI (assuming the President and Congress haven't previously cut it) as the big project that will keep the agency's engineers busy for the foreseeable future. An additional strong source of support for the SEI within NASA is that many people in the agency personally believe that human expansion into the solar system is a worthwhile goal.

There is still some opposition to the SEI within the space community, though. Space scientists are wary of the new initiative because it "relates to

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[50]Eddie Mahe, "The American Public and Space Exploration", Leaving the Cradle: Human Exploration of Space in the 21st Century, 28th Goddard Memorial Symposium, San Diego: Univelt Inc., 1991.

space science and could be seen as competing with science missions for a slice of the constrained budget pie."[51] (Planetary scientists, especially those interested in the Moon and Mars, however, generally support the SEI, including its human exploration aspect.)[52] Proponents of smaller projects within the space program may be worried as they have seen how major initiatives in the past have run over budget and made up the overruns by cutting into the budget of smaller projects. Overall, though, NASA is likely put its clout behind the SEI more and more as time goes on.

The Department of Defense

The Department of Defense could potentially play a large role in the future of the SEI, but its interest in the initiative has not been strong so far. While the DoD has placed a deputy within the Office of Exploration and the Defense Space Council cautiously endorsed the SEI in 1990,[53] the DoD did not request any funding for exploration in 1993. The main reason for this is that the DoD is currently trying to direct its diminishing funding towards projects that it believes are essential for national security. As there are currently no pressing defense needs for the major hardware items needed by the SEI, there is little departmental support for pursuing them.

If a military need were to develop for some of the hardware needed by the SEI, the DoD could potentially fund its development and then share the results with the SEI. It is more likely, though, that rather than developing technology, the DoD may eventually take responsibility for certain tasks

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[51]Susan E. Walker, "Scientists Wary of Exploration Plan", Space News, November 18-24, 1991.
[52]Douglas Isbell, "Science Battles Finance in Exploration Debate", Space News, April 15-21, 1991.
[53]Andrew Lawler, "Defense Panel Backs Plan To Explore Moon and Mars", Space News, April 2-8, 1990.

within the SEI for which it has the appropriate expertise. For example, the Defense Mapping Agency might take the responsibility for the mapping of the Moon and Mars. In a similar vein, the Army Corps of Engineers might work on the planning, logistics, and base maintenance for lunar and Mars bases. Other possible roles for the DoD might include handling communication and navigation functions.

The Department of Energy

Groups within the Department of Energy have already shown considerable interest in working on the SEI. The DoE's role has so far been restricted by Congress to development of space nuclear power sources, but the DoE has been aggressively attempting to broaden its stake in the initiative. The department created an Office of Space in late 1991, and received $5 million for exploration-related research for 1992 (in addition to its ongoing space power programs).[53] If it is successful in receiving a significant amount of SEI-related funding, the DoE could add its clout to NASA's when trying to influence Congress and the President in favor of the SEI

Aerospace Industry

The U.S. aerospace industry could possibly play a major part in the future of the SEI. Currently, though, most companies are waiting for Congress to show a commitment to the SEI before they put either money or effort into the exploration endeavor. The hope of very large contracts in the future has led a few companies to begin to conduct exploration-related studies and research, though, and some companies have even established

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[53]Andrew Lawler, "DoE Exploration Role Restricted", Space News, August 19-25, 1991.

relationships with construction companies with an eye to possible future work on the Moon's surface.[55] A few companies have been promoting the SEI,[56] but significant lobbying is not likely to begin until the awarding of large contracts seems imminent. If the SEI does grow large enough to start letting a significant number of contracts, the aerospace industry will probably become a powerful ally.

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[55]Leonard David, "Congressional Apathy to Moon-Mars Deters Industry Efforts", Space News, September 24-30, 1990.
[56]Debra Polsky, "Aerospace Industry Antes Up", Space News, April 15-21, 1991.

III. The Russian Space Program

Any evaluation of the potential for future use of Russian space hardware requires a solid understanding of the overall Russian space program. It is necessary to know not only the performance characteristics of a particular piece of hardware, but also its history and its place within the broader context of the space program. From this information can be determined the hardware's reliability, its potential for improvement, its likely supporters in the public, government, and industry, and the likelihood that it will continue to be produced in the future.

A Brief Survey of Russian Space Hardware

Launch Vehicles

Laboratories in the Soviet Union began producing small rockets in the early 1930s. After the Second World War, a large rocket program was initiated which built upon both this earlier experience and the knowledge gained from testing captured German A-4 rockets. By the early 1950s, the Soviets were launching various payloads, including dogs, to heights of up to 100 km on the 'Pobeda' or 'Victory' rocket, an improved version of the A-4. In August 1957, the Soviets launched their first intercontinental ballistic missile (ICBM); Sputnik was launched into orbit by the same booster later that year.

The rocket that launched the first Sputniks, the R-7,[57] had a central core of four liquid oxygen (LOX)/kerosene RD-107 engines and four strap-on units, each with four LOX/kerosene engines. The R-7, which was able to deliver 1300 kg into a low orbit, was used three times during the 1957-1958 period, after which a small LOX/kerosene upper stage was added to the design. This improved version, the Vostok, was able to launch 4730 kg into a low orbit and small payloads to Earth escape trajectories. The Vostok has been launched about 150 times, but the launch rate has recently dropped to about one every two years.

Two more variants of the R-7, the Soyuz and the Molniya, were introduced in 1961 and 1963 respectively. The Soyuz and the Molniya have a more powerful second stage than the Vostok, and the Molniya incorporates an additional third stage. The Soyuz can deliver a 7000 kg payload into a low orbit, while the Molniya can deliver 1500 kg payloads into lunar trajectories. The Soyuz and Molniya launch vehicles are still currently in heavy use; about 1500 have been launched to date, with an approximately 95% success rate for each launcher. Most Soyuz launches are of photoreconnaissance satellites, but it is also used to launch biosatellites and the Soyuz and Progress spacecraft. The Molniya, which once launched small lunar and interplanetary probes, is now used to launch early warning and Molniya communications satellites.

The "Kosmos" rocket joined the Soviet stable of launch vehicles in 1964. It is a two-stage vehicle, with an N_2O_4/unsymmetrical dimethylhydrazine (UDMH)-fueled SS-5 missile as a first stage and an

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[57]There are various nomenclatures for Soviet launch vehicles. Wherever possible, I use the Soviet name for the vehicle. If the Soviet name is unknown, the generally accepted Sheldon name for the vehicle is used.

N_2O_4/UDMH-fueled second stage. The Kosmos, which can lift 1,350 kg to a low orbit, has been launched close to 400 times since 1964, with a success rate above 98%. As the average weight of new satellites increases beyond the Kosmos' capabilities, its launch rate has declined, but it is still used to launch low-altitude navigation and communication satellites.[58]

The "F" booster, which was derived from the SS-9 missile, was first used for fractional orbital bombardment tests in 1966. The basic vehicle, the F-1, is a two stage vehicle which uses N_2O_4/UDMH fuel, and has often been used to orbit payloads which incorporate additional propulsive stages. The F-1's estimated payload capacity to a low orbit is about 4000 kg. The Tsyklon version of the "F" booster, which was introduced in 1977, has an additional small third stage which can be restarted three times, enabling the booster to deliver multiple payloads to different orbits. The Tsyklon is advertised as being able to put 4000 kg into a low orbit (though the U.S. DoD believes its real capacity is 5500 kg)[59] and has compiled a 99% success rate over some 200 missions. The F-1 is now used only to launch ocean surveillance satellites; the Tsyklon is used to launch remote sensing, communications, weather, electronic intelligence and geodetic satellites.

The Proton booster, first launched in 1965, was the first Soviet launch vehicle not based on an ICBM. There have been three versions of the Proton, the last two of which are still in use. The original Proton, which flew only four times, was a two-stage vehicle with six engines on the first stage and four on the second; it could lift 12,200 kg to a low orbit. Like all Protons, it used the new N_2O_4/UDMH-fueled RD-253 engine. The next two versions of the Proton, which are still in use, debuted in 1968. The first of these to launch

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[58]Nicholas Johnson, The Soviet Year in Space 1988, Teledyne Brown Engineering, 1989, p.12.
[59]Nicholas Johnson, The Soviet Year in Space 1988, Teledyne Brown Engineering, 1989, p.13.

was a three-stage vehicle able to deliver 20,000 kg to a low orbit. This launch vehicle, which incorporated a third UDMH/ N_2O_4 stage, has been used over the years to launch large payloads, including all of the program's space stations, into orbit. The third type of Proton incorporated both the UDMH/N_2O_4 third stage and a LOX/kerosene fourth stage, and has been used to launch geosynchronous remote sensing and communications satellites and interplanetary spacecraft. The Proton had compiled a 87.7% success rate through 187 launches by 1990, but most of its failures occurred during the first few years of operation. Plans exist to increase Proton launch capacity 10% in the next two years.[60]

The Zenit booster, first launched in 1985, was the first completely new Soviet launch vehicle since the Proton. This vehicle, which boasts a highly automated assembly and launch, is a two-stage LOX/kerosene rocket that can deliver 13,740 kg to a low orbit; its first stage doubles as the strap-on booster for the Energia heavy lift vehicle. A three stage Zenit has been developed, but has never been launched; the third stage would use a LOX/kerosene engine similar to the Proton fourth stage. The Zenit's first fourteen launches were successful, but it has failed three times in attempts to launch since 1990. Its payloads to date have mostly been electronic intelligence satellites, but it is intended to eventually take over the Soyuz booster's space station support tasks.[61]

The Energia launch vehicle, currently the world's most powerful booster, was first launched in 1987. The Energia's core has four LOX/liquid hydrogen (LH_2)-fueled engines; it is the first Soviet launch vehicle to use this

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[60] Peter B. deSelding, "Russians Select Mir as Funding Priority", Space News, March 16-22, 1992.

[61] Steven J. Isakowitz, International Reference Guide to Space Launch Systems, American Institute of Aeronautics and Astronautics, 1991, p. 170.

highly energetic propellant combination. It also has four strap-on LOX/kerosene propellant engines, which are identical to the first stage of the Zenit launch vehicle. The Energia is able to launch either a large cargo carrier or the Buran space shuttle; to date it has been launched once in each of these configurations. Using the cargo carrier, the Energia is able to put an 88,000 kg payload into a low orbit. Various plans for alternate versions of the Energia have been developed. These include a smaller version, the Energia-M, with only one core engine rather than four, which could put 40,000 kg into a low orbit, and larger versions with up to eight strap-ons and a taller core, which could deliver up to 200,000 kg into a low orbit.[62]

Additional space launch vehicles might be developed from the Russian ICBMs that would otherwise be destroyed due to arms control agreements. One proposed launch vehicle is the "Start" vehicle, which would be developed from the SS-20 missile. The Start is envisaged to be a three-stage solid-fueled rocket with the capability to deliver about 200 kg to a 500 km altitude orbit.[63] Plans to develop a launch vehicle from the SS-24 missile have also been put forth; this vehicle would be air-launched from an An-124 aircraft and could deliver a 500 kg payload into a 600 km altitude orbit.[64] Finally, there have been proposals to use SS-18s, the Soviet Union's largest ICBMs, as launch vehicles.[65] An SS-18-derived launch vehicle could be expected to have about twice the payload capacity of the SS-24-derived launcher, though officials of KB Yushnoye, where the SS-18 is built, claim

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[62]Steven J. Isakowitz, International Reference Guide to Space Launch Systems, American Institute of Aeronautics and Astronautics, 1991, p. 119.

[63]"Missiles Have Been Cut Back...and Sent into Space", Krasnaya Zvezda, January 10, 1991.

[64]Peter B. de Selding, "Soviets Seek Partner For Launch Business With Refitted SS-24s", Space News, September 23-29, 1991.

[65]Andrew Lawler, "Teller: Use Ex-Soviet Missiles to Put Brilliant Eyes in Orbit", Space News, March 30-April 5, 1992.

that an SS-18-derived launch vehicle would be able to launch 8,000 kg into orbit.

Table III-1 summarizes some of the performance characteristics of the existing and planned launch vehicles of the Russian space program.

Table III-1: Russian Launch Vehicles

Launch Vehicle	First Launch	Payload to 200 km (kg)	Payload to Escape (kg)	Launch Sites[66]	Reliability since 1970[67]
Vostok	1959	4730	435	Bai, Ples	99 %
Molniya	1961	-	1500	Bai, Ples	95 %
Soyuz	1963	7,000	-	Bai, Ples	98 %
Kosmos	1964	1,350	-	Bai(?), Ples, K.Y.(?)	96 %
F-1	1964	4,000	-	Bai (?), Ples	98 %
Proton	1965	17,000	5,700	Bai	92 %
Tsyklon	1977	>4,000	-	Ples	97 %
Zenit	1985	13,740	-	Bai	80 %
Energia	1987	88,000	30,000	Bai	100 %
Proton Upgrade	1993(?)	(?)18,700	(?)6,270	Bai(?)	-
Converted ICBMs	1995 (?)	(?)200 - (??)8000	-	?	-
Zenit-3	1993 (?)	-	(?)4,300	Bai(?), C.York(?)	-
Energia-M	(?)	40,000	?	Bai(?)	-
Largest Energia Mod	(?)	200,000	?	Bai(?)	-

Propulsion Hardware

The Soviet space program developed a large range of rocket engines to power its fleet of launch vehicles. These rocket engines range from the low-

66The launch sites are Baikonur Cosmodrome (Bai), Plesetsk Cosmodrome (Ples), Kasputin Yar (K.Y.), and the proposed Cape York launch site. These sites are described in more detail later in this chapter.

67All numbers are approximate. Numbers in the literature vary, primarily due to differing definitions of 'success'.

technology RD-107 engines, which were developed in the 1950s, to the powerful new RD-170 engine, to advanced propulsion devices that have not yet been flown. As these rocket engines could very conceivably be used separately from the launch vehicles they power, it is useful to examine them as independent pieces of hardware.

Table III-2 summarizes the pertinent features of some of the major rocket engines that exist in Russia today.

Table III-2: Russian Rocket Engines

Rocket Engine[68]	Oxidizer/Fuel	Exhaust Speed in Vacuum (m/s)	Thrust (kN)	Times Used[69]
RD -107	LOX/kerosene	3,077 m/s	1,000	5,800
RD -108	LOX/kerosene	3,087 m/s	941	1,450
RD -448	LOX/kerosene	3,165 m/s	55	150
RD -461	LOX/kerosene	3,234 m/s	298	1,300
Molniya 3rd	LOX/kerosene	3,332 m/s	66	275
RD -216	N_2O_4/UDMH	2,852 m/s	864	800
RD-253	N_2O_4/UDMH	3,097 m/s	1,635	1,050
Proton 2nd, 3rd	N_2O_4/UDMH	3,265 m/s	600	900
Block 4	LOX/kerosene	3,448 m/s	85	150
RD-219	N_2O_4/UDMH	2,871 m/s	990	200
RD-170	LOX/kerosene	3,303 m/s	7,906	20
RD -120	LOX/kerosene	3,430 m/s	834	12
RD-8	LOX/kerosene	3,352 m/s	78	12
RD-0120	LOX/LH_2	4,435 m/s	1,962	8
SPT-70	Xenon	15,700 m/s	4×10^{-5}	~ 50
SPT-100	Xenon	15,700 m/s	8×10^{-5}	~ 50
Nuclear rocket	LOX/LH_2	8,820 m/s	20	-

A few of these rocket engines have capabilities that match or exceed the world's best. The RD-107, RD-108, RD-461, and RD-253 bear special notice

[68]There are a few rocket engines for which statistics are not yet publicly available. These include the Kosmos second stage and the Tsyklon 1st and 3rd stages.

[69]The approximate total number of times each type of rocket engine has been used successfully on a launch vehicle

because of their age. All of these rocket engines are over 25 years old, and have been used more than a thousand times. Though their efficiencies (as shown by the exhaust speed) are low, their proven reliability is probably unparalleled in the world. The Energia core rocket engine is notable for its use of the liquid oxygen/liquid hydrogen fuel; it is the only Russian rocket engine to use this highly energetic combination. The SPT-70 and SPT-100 are small electric thrusters that use a magnetic field to acclerate a xenon plasma to very high exhaust speeds. Finally, the RD-170 rocket engine is in a class of its own. It is the most powerful (in terms of thrust) liquid-fueled rocket engine in the world, is highly efficient, and can be throttled at levels from 49% to 102% of its rated thrust.

Three projects to develop advanced propulsion technologies were being pursued in the USSR at the beginning of the 1990s. These efforts were directed towards the development of a supersonic combustion ramjet (scramjet), a tri-propellant rocket engine and a nuclear-thermal rocket engine. These projects could have potentially large payoffs if they are successfully developed into working hardware --the scramjet could eventually lead to a low-cost spaceplane, and the nuclear thermal rocket to a high-speed interplanetary transport. The three projects are in various stages of development; the scramjet and nuclear thermal rocket engine efforts have already produced some working hardware.

The scramjet project's high point to date was the flight of a hydrogen-fueled supersonic combustion ramjet in November 1991. This scramjet reached speeds of approximately 7,000 km per hour, which is still far below the speed of 27,000 km/hour needed to achieve orbit. Although plans to develop a space plane were announced in 1991,[70] it seems unlikely that any such vehicle will be produced in the next decade.

The effort to develop a nuclear thermal rocket has met with considerable early success. Small test versions of a nuclear thermal rocket with very high exhaust speeds have been fired for durations of an hour. The rocket's designers claim that the current engine design can be scaled up to 500 to 1000 kN of thrust, and eventually to several thousand kN.[71] The future of this rocket is uncertain at the moment, though top officials in the Russian nuclear program have called for a joint effort with the United States for further work in nuclear propulsion.[72]

Launch Sites

The Soviet Union's first major rocket launch site was the Kasputin Yar cosmodrome at 48.4° N in southwestern Russia. Kasputin Yar was the site of the test launches of the German A-4 and the early Soviet rocket tests. The cosmodrome was closed in 1953, but reopened in 1962 for launches of 'B' and Kosmos rockets and 'Vertikal' suborbital rockets. The launch rate from Kasputin Yar slowed to zero or one per year in the mid-1980's and may have completely stopped.

Construction of the Baikonur Cosmodrome was initiated in May 1955, in a sparsely populated area of the Kazakh republic at 45.6° N. Baikonur was the site of the flight tests of the Soviet Union's first intercontinental ballistic missile and the triumphant orbiting of Sputnik, by the same booster, later

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[70] Moscow Radio Moscow World Service,, 1200 GMT, July 4, 1991.

[71] Joseph R. Welch et. al., "Development of Nuclear Rocket Engines in the USSR", Presented at AIAA/NASA/OAI Conference on Advanced SEI Technologies, September 4-6, 1991, p.7.

[72] Leonard David, "Soviets Reveal Work In Advanced Nuclear Rockets, Seek to Share", Space News, September 16-22, 1991.

that year. For most of its existence, Baikonur was the Soviet Union's second busiest launch site, supporting about 30 launches a year since the mid-1960s. Baikonur has multiple launch pads for Vostok, Soyuz, and Molniya class boosters and F-class boosters (though these have not been used since the early 1970s), two pads for the Proton, and three pads for the Energiya. It also boasts a five km landing runway for the Buran shuttle.

The Plesetsk launch site began operations as the Soviet Union's third launch site in 1966. Located at 62.8° N near Archangel in the Russian republic, Plesetsk provides a northern site for polar launches that is not too distant from the populous areas of Russia. Plesetsk has been generally oriented towards the launch of military satellites; it was historically the Soviet Union's busiest launch site, with multiple launch pads for A-class rockets and the Tsyklon and Kosmos launch vehicles. An average of over 60 rockets were launched from Plesetsk every year from 1975 to 1986; this number began to decline in 1986, as satellite lifetimes improved.

In all three launch sites, the launch pads and assembly buildings are linked by rail. All Soviet launch vehicles are assembled horizontally at the launch site then brought out to the launch pad by rail and lifted to a vertical position. In general, the launch vehicles are very robust. They are able to operate under very severe weather conditions, including high winds and snow and it is not uncommon for multiple launches to be conducted on the same day.[73] The number of launches per year has been slowing in recent years, but is still high compared to any other country. Through the 1980s, Soviet launch vehicles placed around 90 satellites weighing 350,000 kg into orbit each year. In 1990, the total was 76 satellites; in 1991 approximately 60.

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[73]Nicholas Johnson, The Soviet Year in Space 1988, Teledyne Brown Engineering, 1989, p.9.

Various proposals have been made over the years to launch Soviet launch vehicles from other launch sites. (As discussed in the next chapter, low-latitude launch sites can significantly increase the payload a launch vehicle is able to deliver to certain orbits.) The most persistent of these proposals has been one to launch Zenit boosters from the proposed Cape York launch site in Australia.[74] The Zenits would be shipped to this 12° S launch site in batches of three or delivered by transport aircraft.[75] Current support for this venture is uncertain, but in any case, launches would not start before 1997.[76]

Humans-in-space Hardware

Using the Vostok booster, the Soviets launched Yuri Gagarin into orbit in April 1961. The spacecraft he travelled in, the Vostok capsule, weighed about 4700 kg and carried only one cosmonaut. It had no maneuvering capability except to return to Earth, and no soft-landing capability; the pilot ejected from the capsule before it struck the ground. The Vostok capsule was followed by the Voskhod, a three seat capsule created by removing both of the Vostok's ejector seats and eliminating the requirement that cosmonauts wear space suits. The Voskhod program marked the debut of non-pilot cosmonauts in space, the first spacewalk, and the first soft-landing of a spacecraft. After two flights, the Voskhod program was cancelled to make way for the Soyuz.

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[74]Jon Fairall, "With CSYA Down, Australians Hopeful on Spaceport Plan", Space News, November 4-10, 1991.

[75]Steven J. Isakowitz, International Reference Guide to Space Launch Systems, American Institute of Aeronautics and Astronautics, 1991, p. 178.

[76]Robina Riccitiello, "Zenit Failure may Hinder Russian Sales Campaign", Space News, March 30-April 5, 1992.

The Soyuz capsule was originally designed to be part of a Soviet manned lunar program. The hardware for this plan was given the name 'Soyuz', or union, as it was to involve the linking together of a number of spacecraft in Earth orbit. The Soyuz capsule was the only piece of hardware retained from this original plan, though two other pieces of manned lunar mission hardware were flown in the late 1960s and early 1970s. These were Zond 1, a 5300 kg orbital module designed to take one cosmonaut around the Moon, and the heavy Zond, a 10,500 kg three-cosmonaut vehicle which was intended to be used as part of a manned lunar landing program.[77] One legacy from the Soyuz capsule's lunar heritage is its capability to re-enter the Earth's atmosphere safely at the high speeds characteristic of a direct return from the Moon.

The initial Soyuz capsule weighed 6575 kg at launch. It was composed of three modules with a total habitable volume of about 9 cubic meters. One of the three modules was unpressurized and contained maneuvering engines, fuel, supplies and the solar arrays. The two habitable modules were the command module, occupied during ascent and descent, which contained control panels and three seats for cosmonauts, and the orbital module, which contained the spacewalk hatch and lockers for food, equipment, and experiments.[78] The Soyuz had the capability to rendezvous and dock with another Soyuz spacecraft either automatically or when piloted. It, like all Soyuz capsules to date, was capable of making water landings, but, as a rule, soft-landed on dry ground.

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[77]Brian Harvey, Race Into Space: the Soviet Space Program, Chichester: John Wiley & Sons, 1988, p. 85.

[78]Office of Technology Assessment, Salyut: Soviet Steps Toward Permanent Human Presence in Space, U.S. Government Printing Office, December 1983, p.11.

The Soyuz capsule has been redesigned three times since this first incarnation, though all of the spacecraft have had basically the same configuration. The first redesign of the Soyuz came after the death of three cosmonauts in 1971 in an accident where air pressure in the capsule was lost. It was decided after this accident that the cosmonauts should wear spacesuits during ascent and descent; to make up for the increased weight of the spacesuits the third seat, the solar panels and some of the fuel storage were removed. This second model of the Soyuz flew 28 times, 22 times to space stations. (though four of these times, it was unable to dock with the station). This Soyuz had only a three to four day lifetime when not connected to the space station as it had no solar panels. When attached to the station, the Soyuz lifetime was 90 days.

The second redesign of the Soyuz led to the introduction of the Soyuz-T in 1976. This version of the Soyuz once again had solar panels and additional fuel, and the savings in mass and space resulting from the use of microelectronics allowed the reintroduction of the third seat. The lifetime of the Soyuz-T while attached to a space station was demonstrated to be at least 150 days. The docking problems of the earlier Soyuz were lessened with the Soyuz-T, which only failed to dock once, when a rendezvous radar did not deploy. Twice, however, the automatic docking system failed and the cosmonauts were forced to dock manually.

The current incarnation of the Soyuz, the Soyuz TM, was introduced in 1986. It boasts a new navigation and rendezvous unit, new communications and power systems, a 200 kg greater launch payload capacity, and a 70-90 kg greater return payload capacity.[79] It has a lifetime of 180 days when attached

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[79]Nicholas Johnson, The Soviet Year in Space 1987, Teledyne Brown Engineering, 1988, p.83.

to the station, and a maximum lifetime of up to a week when flying separately.[80] By 1992, Soyuz-TMs had flown 13 times without a serious failure, though the automatic docking system has not always worked. Design of a new piloted space capsule was said to be underway in 1991, but it is not clear if and when it will appear.[81]

The other main spacecraft used to support the space station program is the robotic Progress cargo spacecraft. The Progress, which first appeared in 1978, was based on the Soyuz design, but carried fuel and supplies rather than cosmonauts. The original Progress weighed 7,020 kg and could carry about 2,300 kg to the space station, with which it docked automatically. The Progress was first upgraded in 1986 after which it was able to deliver up to 2600 kg of fuel and supplies to the space station. In 1989, the Progress was replaced by the Progress-M, which has an increased lifetime of 30 days as an independent spacecraft or up to 108 days while attached to a space station. Unlike the earlier versions, which had no capability to return cargo to Earth, the Progress-M has a small return capsule, 60 cm in diameter, which is able to return 100 - 150 kg to Earth.[82] The Progress spacecraft have generally experienced much less trouble in docking than the Soyuz spacecraft.

Soviet space stations, the destination of these Soyuz and Progress spacecraft, began to appear after the demise of the Soviet lunar program in the late 1960s. The first Soviet space station, Salyut I, was launched in 1971, and the eighth, Mir, is still in operation in 1992. The first station was designed and

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[80]Michael Parks, "Plight of Soyuz Raises Tough Questions", Los Angeles Times, September 8, 1988.

[81]Boris Olesyuk., "A Personal View: The Price of Our Jaunts Into Space", Kuranty, April 11, 1991.

[82]Moscow Domestic Service in Russian, 1530 GMT, August 25, 1989.

manufactured in in only two years,[83] but its basic design is not very different from that of the core module of the current Russian space station.

The core modules of all the space stations have weighed about 20 metric tons, and have been launched by the Proton rocket into 51° orbits at altitudes of from 241 to 370 km. The core modules have varied from about 13 to 15 meters in length with a maximum diameter of 4.2 meters and a volume (with a Soyuz capsule attached) of about 100 cubic meters. The core modules have each had three sections, two of which were habitable. The habitable sections are a transfer/docking compartment and a working/living compartment; the unpressurized compartment is used for instruments and propulsion.[84] The first five Salyuts were equipped with one docking port, Salyuts 6 and 7 had two docking ports, and Mir has six docking ports.

Salyut 2 did not achieve a stable orbit, but Salyuts 3-7 marked a period of increasing Soviet mission lengths and capabilities in space. Mission lengths increased from 24 days in Salyut 1 to 185 days in Salyut 6 to 237 days on Salyut 7. Two crews visited Salyut 1; ten visited Salyut 7. Various new systems were introduced as the program progressed, including additional solar panels, the Progress cargo module, on-orbit refueling, water recycling, the docking of additional modules to the station cores, and measures to increase the habitability of the station. During the Salyut program, cosmonauts learned how to perform repairs in space and much experience was gained on human performance in space and in space operations, such as docking, extravehicular repairs, and rendezvous.

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[83]Brian Harvey, Race Into Space: the Soviet Space Program, Chichester: John Wiley & Sons, 1988, p. 192.

[84]Office of Technology Assessment, Salyut: Soviet Steps Toward Permanent Human Presence in Space, U.S. Government Printing Office, December 1983, p.15.

The Mir space station, launched in 1986, differs mainly from the earlier stations in having six docking ports. A 5.8 meter long, 4.15 meter diameter module named Kvant, was attached to the station in 1987, along with additional solar panels. Two more core-sized modules, Kvant-2 and Kristall, have been added since then, bringing the station's total habitable volume to about 280 cubic meters. Mir theoretically receives 28 kw of power from its solar arrays, but shadowing and photocell degradation problems mean that the actual power level is closer to 10 kw.[85]

A number of plans for Mir's future have been presented. Plans for expansion include two long-delayed core-sized modules, Priroda and Spektr, to be launched in 1993 or 1994.[86] Other plans have discussed replacing the Mir core module, but keeping some of the expansion modules[87], or replacing the entire station with a new Mir-2 station, built more along the lines of the planned U.S. space station.[88] Adding some urgency to these plans is the fact that the design lifetime of Mir was five years, an anniversary passed in 1991.

The only totally new piloted Soviet spacecraft since 1971, the Buran space shuttle, was launched on its first, and to date only, mission in 1988. The Buran, which resembles the U.S. space shuttle, is launched on the Energia booster, and can be flown either with or without pilots. A payload of 30,000 kg can be delivered from the Buran into a low orbit (the empty orbiter can reach an orbit up to 1000 km) and a payload of 20,000 kg can be returned from orbit. The orbiter provides 30 kw of power and has 70 cubic meters of

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[85]Boris Olesyuk, "Is the Mir Station a Commodity?", Kuranty, February 1, 1992.
[86]Lt. Col. A. Dolgikh, "Let Me Introduce You to Mir Stage Two", Krasnaya Zvezda, August 2, 1991.
[87]Moscow Radio Moscow World Service 0710 GMT August 16, 1991.
[88]Peter B. de Selding, "Officials Plan Longer, Leaner Mir in Late '90s", Space News, October 21-27, 1991.

habitable volume and 317 cubic meters of cargo space.[89] Though the only flight to date had no humans on board, the crew of Buran can reportedly range from zero to ten cosmonauts. Buran's initial maximum mission duration is seven days, but this should be extendable to 30 days after modifications.[90]

Robotic Lunar and Planetary Spacecraft

The Soviets began their lunar exploration program in 1959 when they used the Vostok booster to launch three probes towards the Moon. These probes discovered the solar wind and the absence of a lunar magnetic field, and transmitted back pictures of the far side of the Moon. Failures of the Molniya upper stage and errors in the guidance and control of the probes led to the failure of the next eight lunar probes; The only successful Soviet mission to the Moon between 1960 and 1965 was the Zond 3 Mars probe, which swung by the Moon on the way to Mars in 1965 and sent detailed pictures of the Moon's surface back to Earth.

In 1966, Luna 9 successfully soft-landed on the Moon and sent back pictures of its surface. Two more booster failures were followed by the launch of the first successful lunar orbiter, Luna 10, which operated for 60 days, sending back data from its magnetometer, gamma ray detector, infrared radiometer, cosmic ray detector, and meteoroid counter.[91] These precursor missions mapped much of the Moon, and tested the density and basic chemical composition of the lunar soil. Three sample return missions in the

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[89]Steven J. Isakowitz, International Reference Guide to Space Launch Systems, American Institute of Aeronautics and Astronautics, 1991, p. 111.
[90]Nicholas Johnson, The Soviet Year in Space 1988, Teledyne Brown Engineering, 1989, p.113.
[91]Brian Harvey, Race Into Space: the Soviet Space Program, Chichester: John Wiley & Sons, 1988, p. 106.

late 1960s failed, but were followed by the successful return mission of Luna 16 in 1970. The lunar orbiters and sample return missions continued until 1976, increasing in sophistication over this period --the final sample return mission drilled and retrieved rock samples from two meters below the surface.

The high point of the Soviet lunar program, however, was the two Lunokhod rovers. The first vehicle weighed about 750 kg and measured 2.2 by 1.6 meters; the second was slightly larger. The rovers, which were powered by solar panels and a small radioisotope thermal generator, carried cameras to observe the Moon and sky and instruments to test the strength and composition of the soil. The first Lunokhod survived nearly a year and traveled 10.5 km. The second Lunokhod survived almost six months and travelled 37 km, sending back 80,000 television pictures.

The Soviets also began to operate a planetary program at the beginning of the 1960s. Launch vehicle failures destroyed the first three Mars probes, and contact was lost with the first Venus probe early in its journey. Three more Mars probes were launched in 1962, but the most successful was the third, which experienced an orientation system breakdown when the spacecraft was 100 million km from the Earth. A series of similar mishaps plagued the Soviet planetary program throughout the early 1960s, until by 1966, the Soviets had launched 17 probes to Mars and Venus without a single one completing its mission.

The first partially successful Soviet Mars probes came in 1971, when two probes successfully achieved orbits around Mars. The landers that were to have operated in conjunction with the orbiters, however, were unsuccessful. These probes were followed by two more failures and a success in 1973. (By this time, American planetary probes had overcome their early problems and were more lighter, more sophisticated, and much more reliable than the Soviet probes.) No more Soviet Mars probes were launched until 1988, and in that ambitions mission to Mars and Phobos, both spacecraft failed to complete their mission. Contact was lost with Phobos 1 when an incorrect command switched off the attitude control system, and with Phobos 2 when the onboard computer malfunctioned.[92]

The Soviets had more luck with the exploration of Venus Venera 4 reached Venus and parachuted deep into its atmosphere in 1967. Venera 5 and 6 also reached Venus and parachuted even deeper into its atmosphere in 1969. These successes were followed by a generally successful series of Venus landers and orbiters ending with the Vega spacecraft, which dropped a lander and two long-lived balloons into the atmosphere before going on to observe Halley's Comet in 1986,

Current plans for robotic missions focus on Mars. Two missions with strong international participation are currently under development. The first of these missions, scheduled to leave Earth in 1994, will include an orbiter and a descent module that will deploy several small stationary probes. The second mission, scheduled for 1996, will also include an orbiter and stationary probes, but in addition will carry a robotic rover and a weather balloon.[93] Funding for these missions is far from certain, though other countries involved in the effort have been standing by to subsidize the program if necessary.[94]

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[92]R.Z. Sagdeev & A.V. Zakharov, "Brief History of the Phobos Mission", Nature, October 19, 1989.

[93]William Boyer, "Visiting Russian Rover Team Calls Mars Funds Stable", Space News, June 1-7, 1992.

[94]Peter B. de Selding, "Germany Seeks Cash Infusion to Save Russian Mars Mission", Space News, April 6-12, 1992.

Applications and Space Science Satellites

The Soviet Union has long carried out strong robotic applications and space science programs in Earth orbit. The first Sputniks carried out basic space science tasks, and they were soon replaced with satellites performing military, civil, and scientific duties. Historically, most Soviet spacecraft have been part of these programs, but as they are, in general, not very relevant to the SEI, they will only be discussed briefly.

Most Soviet satellites were launched on military missions, including early warning, photoreconnaissance, ocean surveillance, weather monitoring, navigation, communication, and electronic intelligence gathering. The largest component of the military space program has historically been photoreconnaissance, but the most interesting hardware for the purposes of the SEI is inside the ocean surveillance satellites. To supply the large amount of power needed to detect ships and submarines from space without using large, high-drag solar panels, the Soviets developed a space nuclear power reactor.

Though detailed information on the Soviet space nuclear reactor program has yet to become widely available, the general features of two types of reactors are known. The first of these is a thermoelectric reactor that operated on all RORSATS prior to 1987. This type of reactor weighed somewhat less than 390 kg, used approximately 20-25 kg of uranium fuel, and produced about 1.3 - 2 kw of electricity.[95] The lifetime of these reactors was probably short; no RORSAT using them had lasted for more than six months. The second type of reactor is the Topaz thermionic reactor, which was first tested in space in 1987. These reactors weighed around 1000 kg, used about 12

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[95]Gary L. Bennett, "A Look at the Soviet Space Nuclear Power Program", Proceedings of the 24th Intersociety Energy Conversion Engineering Conference, Vol 2, August 6-11, 1989.

kg of Uranium 235, and produced approximately 10 kw of electricity. The lifetimes of the two test satellites that used these reactors were six months and one year.

Finally, in addition to the military satellites, the Soviets have also launched many space science and civil applications satellites. Applications satellites launched have included communication satellites, weather satellites, and earth resource monitoring satellites. Numerous scientific satellites have carried out astronomical and space environment research as well as microgravity research and production. Soviet scientific instruments have also been carried on satellites performing other tasks and on the Salyut and Mir space stations. In general, Soviet applications and scientific satellites are notable for being less complex than Western satellites and for having shorter operational lifetimes.

The Russian Space Program: An Institutional Perspective

Considering the current conditions within Russia and the uncertain relations between the Russian republic and the other states which once made up the Soviet Union, it is not yet clear what the final shape of the Russian space program will be. An examination of the institutional structure of the former Soviet program, and of how the changes of the past few years have influenced both the structure and its constituent parts, however, enables the creation of of some educated hypotheses about the program's future direction.

By the end of the 1980s the Soviet space program was a vast and complex enterprise composed of approximately a thousand design bureaus (KBs), scientific research organizations (NPOs), and factories, employing a total of around a million workers.[96] No national laws on space existed, and the program's many component organizations interacted with each other through a complex web of overlapping authorities, both official and unofficial.

An attempt could be made to fit the Soviet space program into a standard organization chart based on the official connections between the major bodies involved in the program. At the top of this chart would be the CPSU Central Committee Secretariat (the Politburo), which was expected to make major decisions on space programs and policy. Below the Politburo would be the USSR Council of Ministers' State Commission for Military-Industrial Affairs, which, guided by a five-year plan, was supposed to handle the high-level management and coordination between all the ministries and departments involved in space activities. This Commission, in turn, had authority over the space efforts of the Ministry of General Machine Building, and the Defense Ministry. The Defense Ministry was in charge of tracking satellites, cosmonaut training, and the nation's launch sites, while the Ministry of General Machine Building was in charge of developing and building the nation's space hardware, through its many KBs and NPOs.

There were an estimated thousand NPOs, KBs and institutes performing work on the Soviet space program. The largest bureau was NPO Energia, which had prime responsibility for the Energia launch vehicles, operation of the Mir space station, and many other large tasks. Estimates are that over the last 10 or 20 years, 60% of the money spent on the Russian civilian space program went through this bureau.[97] Another major bureau

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[96]Andrey Tarasov, "Club 206: Into the International Space Year on the Fragments of the Space Program", Literaturnaya Gazeta, January 22, 1992.

[97]Peter B. deSelding, "Bargain Prices Build Russian Resentment", Space News, April 27-May 2, 1992.

was the military-oriented Central Specialized Design Bureau (CDSB), which manufactured the Soyuz, Molniya, and Vostok launch vehicles, as well as scientific and Earth observation satellites. Other Russian space bureaus included KB Machine Building, KB Salyut, which built the space stations, NPO Molniya, which produced the airframe for the Buran space shuttle, and TsNMIIMash, the Central Scientific Research Institute of Machine Building, which ran the Soviet Flight Control Center. The largest bureau outside Russia was KB Yushnoye in the Ukraine, which built the SS-18 and SS-24 missiles and the Tsyklon and Zenit boosters (though the rocket engines for these vehicles are manufactured in Russia at NPO Energomash).[98]

A few more organizations would have positions to the side of this chart. The semi-independent USSR Academy of Sciences had the task of proposing space science missions and coordinating international activity via the Interkosmos Council. The Ministry of Health had a small role in space life sciences and life support. A number of state commissions, such as the State Commission for Flight Tests of Manned Space Complexes, had an oversight role for particular parts of the program. Some high level bodies, such as the Ministry of Defense, the USSR State Committee for Hydrometeorology and the USSR Main Administration of Cartography, were customers for space products.

In reality the organization of the Soviet space program was far more complex than such a chart would suggest. The various technical and operational units of the Soviet space program were created in a haphazard manner, accumulating as the space program itself grew. Numerous committees and commissions were formed over the years to coordinate these

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[98]Colonel M. Rebrov, "Profile of a General Designer: The Owl of Minerva Appears at Night", Krasnaya Zvezda, March 23, 1991.

units, but these generally had no power. Personal and institutional prestige and contacts, rather than the official role of a particular organization, tended to determine where that organization fit into the Soviet space program. For example, while the famous 'Chief Designer' Sergei Korolev was alive, his design bureau set the main direction of the space program. Korolev's position was strengthened by his contacts in the Politburo and his alliance with 'Chief Theorist' Keldysh of the USSR Academy of Sciences.

Importantly, there was no real central authority for the USSR's space program. (One long-time observer managed to identify seven bodies with official responsibility for determining the direction of the Soviet space program.)[99] The lack of any coordinating agency for space led to a situation where the organization in charge of developing new hardware (the Ministry of General Machine Building) was also in charge of determining what hardware was needed. One apt description of the space program was that it was "kind of a state within a state, which, in the process of its development, is pursuing its goals, which are known only to it."[100]

While there were some cases where a customer for space services did have a strong role in the development of space hardware (the Ministry of Defense is perhaps the best example), in general the developers had the upper hand. For example, though the USSR Academy of Science was supposed to be in charge of the space science program, the reality was more often that a spacecraft would be developed and then the space scientists would be asked whether or not they wanted to use it.[101] The main reason for this situation was that assets for most civil space programs were allocated directly to the

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[99]Yaroslav Golovanov, "Just Where Are We Flying To?", Izvestiya, December 12, 1991.
[100]Vladimir Terekhov, "Points of View, Discussions and Evaluations", Sovetskaya Rossiya, August 22, 1990.
[101]K. Gringauz, "Loss of Escape Velocity", Pravda, March 25, 1989.

developer of the space hardware, rather than to the customer The hardware developer then had the power to specify what equipment would be installed and where the results would be sent.[102]

In the late 1980s, a number of trends which strongly affected the Soviet space program began to become apparent. These trends were:

- a change in the nation's attitude toward space, spurred on by glasnost,
- a reduction in spending on space from the central government, and
- the conversion of space factories to commercial goods production.

The trends tended to reinforce each other, and they continue to strongly influence the Russian space program today.

The most obvious of these trends was that of the changing national opinion toward the space program, spurred on by the policy of 'Glasnost' (openness). Since the launching of Sputnik, the Soviet space program had been used by the government as a propaganda tool. Failures were hidden, successes were lauded, and the many benefits of the space program were repeatedly trumpeted in the press. Public cynicism and disillusionment, however, had led many in the Soviet Union to doubt anything the government said, including its pronouncements about the wonders of the space program. With the coming of Glasnost, this dissatisfaction began to be heard, and by the late 1980s, it became clear that the public did not believe what it had been told about the economic benefits of the space program.[103]

Public dissatisfaction with the space program might not have had any effect, but the economic troubles of the late 1980s resulted in less money being available in the country. By 1989 public opinion seemed to support sharp

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[102] B. Konovalov, "A Space Agency is Needed", Izvestiya, February 1, 1991.

[103] "Interview with Chief of Glavkosmos A.I. Dunayev", Sotsialisticheskaya Industriya, October 3, 1987.

cutbacks in the space program,[104] and the government began to push the concept of "khozraschet" or economic accountability on the organizations involved in the space program, forcing them to show some results from the money that was being spent on space. The initial reaction from space organizations was to bring up dubious figures showing the economic return from existing space programs, and of 'spinoffs' of those programs.[105,106]

The effort to squeeze economic returns from the space program began to be felt by the space organizations as money for space programs dried up. In 1990, the government granted some of the larger organizations within the Ministry of General Machine Building the right to independently sign space cooperation agreements with organizations from other countries,[107] but their attempts to sell space services to other nations were generally stymied by restrictive U.S. policies and the business inexperience of the Soviet organizations. Cash-strapped organizations thus had to find a way to make money selling products other than space equipment.

During this period, the government was also trying to increase the production of consumer goods, which were in poor supply throughout the Soviet Union. As the space organizations were unable to make money selling space services, the government set many of them to producing consumer goods. The strong government support for this policy is evidenced by the 1989 visit of the secretary of the Communist Party Central Committee to NPO Energia to "draw particular attention to the need to speed up work to

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[104]Vitaliy Golobachev, "What We Are Finding, What We Are Losing", Trud.

[105]A. Rodionov, "Readers Conduct the Interview: Why Are We Going Into Space?", Trud, January 26, 1989.

[106]V. Kh. Doguzhiyev, "Examined in the Presidium of the USSR Council of Ministers: Space Outlays and Returns", Pravitelstvennyy Vestnik, May 1989.

[107]V.S. Avduyevsky and L.V. Leskov, Where is the Soviet Space Program Going?, Moscow: Znanie, 1990.

supply to other economic sectors the scientific and technical achievements [of the NPO]."[108] The Ministry of General Machine Building was charged with the development of modern equipment for enterprises such as bakery, soap-making, sugar-refining, and the manufacture of prostheses and disposable syringes, as well as transferring any spinoffs to Ministries that needed them.[109]

The next major change for the space program came with the breakup of the USSR into its constituent republics. Though somewhere upwards of 80% of Soviet space assets are concentrated within the Russian republic, two major facilities are outside its borders: the Baikonur launch site and KB Yushnoye, the factory that produces the Zenit and Tsyklon launch vehicles. Other problems raised included the questions of who owned the satellites already in space, whether international agreements made by the USSR were still valid, and how the space program would be reorganized to conform to this new situation.

After some initial problems, a number of agreements on cooperation between the former Soviet republics have been signed, but these have generally been vague documents aimed at allowing the space program to continue operations. In the first major agreement, on December 30, 1991, nine of the former Soviet republics signed an agreement on the Commonwealth of Independent States (CIS) space program, putting the commonwealth's military space program and joint use programs under the direction of the strategic armed forces and its civil space programs under an interstate space council. The agreement mentioned the "need for rigorous

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[108] "Space Geared to the Economy", Pravda, February 8, 1989.

[109] V.S. Avduyevsky and L.V. Leskov, Where is the Soviet Space Program Going?, Moscow: Znanie, 1990.

observation of international agreements and obligations,"[110] and barred Kazakhstan and the other republics from interrupting the functioning of Baikonur Cosmodrome. More agreements on space were signed in 1992; on May 10, the leaders of ten of the former republics agreed to fund civil space activities jointly, and on May 26, Russian President Yeltsin and Kazakh President Nursultan Nazarbayev discussed the future of the Baikonur Cosmodrome and, according to the head of the new Russian Space Agency, "all restrictions and restraints" on its use were removed[111]

It is highly doubtful that these agreements represent the last word on any of the issues raised by the dissolution of the Soviet space program. For example, the December 30 document created a CIS space program, but it is not known if the CIS itself will survive, or whether it will have any power if it does. In addition, the agreement did not resolve the main points of financial and operational responsibility for space among the republics.[112] Finally, two republics, Ukraine and Moldova, did not sign the agreement.

There have also been a number of reorganizations inside Russia. First, the Ministry of General Machine Building was reformed as the Russian General Machine Building organization, a new organization which includes all the Russian organizations within the old MGMB except for NPO Energia.[113] Second, a Russian Space Agency, headed by Yuri Koptev, former Deputy Minister of the MGMB, was set up in February 1992, with authority

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[110]Vincent Kiernan, "Minsk Accord Struck on Space", Space News, January 6-12, 1992.

[111]Vincent Kiernan and Andrew Lawler, "Koptev Confident About Russian Space Program", Space News, June 15-21, 1992.

[112]Peter B. deSelding, "Russian Bureaus Await Yeltsin Nod for Reorganization", Space News, February 10-16, 1992.

[113]Andrey Tarasov, "Club 206: Into the International Space Year on the Fragments of the Space Program", Literaturnaya Gazeta, January 22, 1992.

over all Russian civil space activities.[114] Under this new scheme, the Defense Ministry will control all military space assets and cooperate with the civil agency in areas such as spacecraft tracking and telemetry. The civil space program will operate the Mir space station, planetary efforts, and launch programs relating to human missions.[115]

Despite all the tumult in the political and economic environment, much of the space program has yet to change dramatically. The abolition of the Soviet Union did not result in the end of the Soviet space program; with few exceptions the same people reported to the same jobs after the breakup. Money that used to flow through the Ministry of General Machine Building to build satellites may now go directly to the NPO involved in building the satellite, but in general, it has not been stopped entirely. The fact that some space enterprises are now divided by national boundaries has not prevented them from continuing to work with one another. Slowly, however, the shrinking amount of money available is inexorably forcing organizations to change to meet the new conditions .

The Future of the Russian Space Program

The Overall Shape of the Future Program

The future of the Russian space program is far from clear. Before its final form can be predicted with any hope of accuracy, it will be necessary to know:

- how much Russia is prepared to pay for the space program,
- how the shrinking of the space program will be managed,

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[114]Boris Konovalov, "Russian Space Agency Set Up", Izvestiya, February 28, 1992.

[115]Vincent Kiernan and Andrew Lawler, "Koptev Confident About Russian Space Program", Space News, June 15-21, 1992.

- how the former Soviet republics will interact with each other, and
- the scope of international intervention in the program.

Until these questions are answered, the future of any particular piece of space hardware will be very uncertain.

Perhaps the most important of the questions is how much money Russia is going to pay to support its space program, which will determine the overall program's overall size. According to Yuri Koptev, the head of the new Russian Space Agency, Russian President Boris Yeltsin is a strong supporter of the civil space program.[116] There, however, a couple of factors which make it almost certain that the space program is going to decline in size. First, the space program is not very popular with the people, many of whom see it both as waste of money and as a relic of the Communist past linked with the military-industrial complex. Second, and more importantly, the declining Russian economy seems likely to lead to decreases in the amount of money available for the space program.

How the shrinking of the space program is managed will also have a lot to do with what parts of it survive. Though inefficiencies due to the program's former Byzantine organizational structure and secrecy are large, the savings from eliminating them (even if such a feat is politically possible) will probably not be large enough to make up for funding reductions; it seems certain that some real cutting of programs will have to be done. As one observer stated, "there are just too many design bureaus, institutes, and factories involved in the space business. Over the long term, some of them are going to go away and those capabilities can't be retrieved again."[117]

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[116] Vincent Kiernan and Andrew Lawler, "Koptev Confident About Russian Space Program", Space News, June 15-21, 1992.

[117] Leonard David, "U.S. Firms Ponder Dealings with Former Soviet Union", Space News, May 4-10, 1992.

This pruning of the space program could be carried out in a number of ways, each with its collection of potential pitfalls. The program could just be allowed to slowly decline, as it has been doing for the last three years, but this is unlikely to result in either a strong space program or space industry. Alternatively, the program could be forced to operate on a fairly capitalistic basis, but this might result in the loss of prestigious programs that do not have tangible financial payoffs. Finally, the government could pick and choose which organizations and capabilities will be maintained and which cancelled; the pitfall here is that the choice may be dominated by political, rather than technical, economic, or policy-related factors. Early efforts to prioritize national space efforts are being conducted by a 50-member commission headed by the president of the Russian Academy of Sciences, but it is not clear how much weight the commissions reccomendations will have.[118]

The third major question on which the future of the Russian space program rests is what the future relations between the former Soviet republics (most importantly Russia, the Ukraine, and Kazakhstan) will be like. Less than cordial relations between Russia and Ukraine could result in the demise of the Zenit booster, for example; troubles with Kazakhstan could result in Russia being forced to rely heavily on the Plesetsk Cosmodrome (and the boosters that can be launched from there). The decision of who will operate the military space programs will determine their size and composition. Finally, unless some way for all (or at least most) of the republics to pay for the overall space program is found, spending cuts will be very deep.

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[118]Vincent Kiernan, "Russia to Prioritize National Space Activities", Space News, August 24-30, 1992.

Large scale cooperative efforts with the space agencies of other nations could also have an effect on the final shape of the Russian space program. For example, Russia has applied to join the European Space Agency (ESA).[119] If this application were to be accepted, Russian capabilities useful for a joint ESA-Russia space program would probably be maintained, while Russian programs that duplicate European capabilities might be cancelled. In a more likely scenario, ESA may pursue some cooperative projects with Russia, thus helping to preserve the existence of the hardware involved in those projects. The United States also has the opportunity to affect the destiny of the Russian space program; a large U.S./Russian program of cooperation in the SEI, for example, could lead the Russians to concentrate on maintaining the capabilities that would be needed for such an endeavor.

The Future for Particular Space Systems

It is clear that to guess which pieces of hardware might still be available a few years from now is a very risky proposition. The best that can be done is to examine each item of hardware in terms of the following criteria:

- its place in the overall space program
- its costs and benefits to the rest of the economy,
- its value for national security,
- its value for national prestige, and
- the political clout (and survivability) of its manufacturers and users.

[119] Peter B. deSelding, "ESA, Russians in Courting Ritual", Space News, April 6-12, 1992.

The extent to which each of these factors is important will depend on the overall shape that the Russian space program takes, as described in the previous section.

The first criterion, the place of the hardware in the overall space program, is quite important. It's unlikely that the Soyuz launch vehicle will be phased out, for example, as it is the only Russian booster that has launched humans into space in the last quarter-century. On the other hand, the Vostok, which really has no payloads, could easily be completely cancelled. This criterion is likely to be more important if the management of the space program is given a strong hand to reorganize.

The second criterion, costs and benefits to the rest of the economy, should be very important in the decisions over which hardware will remain. The Buran shuttle, for example, seems unlikely to fly again because it fails both this criterion (in being very costly and having no economic benefits) and the previous criterion (in that it has no payloads). Systems, such as communications satellites, which are providing necessary services to the nation, however, are more likely to continue being produced. One crucial point is that this is one criterion that can be affected by forces outside the USSR. While the current situation, in which minute amounts of foreign currency make a large difference in the survivability of a particular piece of space hardware, is not likely to continue for long, it does seem probable that modest financial support (or even the promise of such support) might be enough to keep some items of hardware from being lost.

The third criterion, the value of the hardware to national security, might apply to either the security of the Russian republic, or to whatever inter-republic system ends up operating the former Soviet Union's military space systems. While it seems very clear that the military is going to shrink significantly, it is likely that at least some military space systems will remain. Hardware that is either part of these systems, or is used to support them will be unlikely to be cut. Some examples of hardware that might be preserved for their use in the military space program are the Tsyklon launch vehicle and the Topaz reactor.

The fourth criterion used to judge whether or not a space system might keep operating is its value for national prestige. Again, this might be the prestige of the Russian Republic, or of whatever confederation may be running the space program. In either case, there is strong evidence that, despite the fact that space is not very popular in Russia, there is resistance to completely giving up the country's former leading position in space. The prestige factor is most likely to be important in the humans-in-space programs, as they have the greatest political value, but this criterion may also help save some space science hardware.

The final criterion, the political clout of the manufacturers and users of a particular piece of hardware, will no doubt play an important role. For example, it will be easier to kill a system built in a plant in another republic than in a plant near the capital. There will also be pressure not to kill a plant's major project, lest the cancellation causes the entire organization to collapse. Large organizations, such as NPO Energia, might have enough clout to save the hardware they are working on, or at least to decide which of the projects they're working on they want to continue. (NPO Energia's power to influence the future of the Russian space program was recently illustrated by its contribution of a billion rubles towards the effort to keep Baikonur Cosmodrome in operation.)[120] If nobody is given strong authority over the

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[120]Peter B. de Selding "Republics to Share Profits From Mir", Space News, August 10-16, 1992.

future of the Russian space program, the influence of manufacturers and users is likely to be the most important criterion for determining which hardware will survive.

As a final note, even if a piece of hardware is cancelled, it will generally take some time before the loss becomes irreversible. The ability to bring a piece of hardware "back" depends on the condition of the equipment used to manufacture it, the ability to retain the workers who know how to build and operate the hardware, and the availability of all the necessary documentation. The policy of "conversion," for example, has generally not yet resulted in the loss of the machinery used to produce space hardware, as most plants have continued to maintain it. The biggest problem caused by conversion has rather been the loss of the highly trained specialists, who have left as technical tasks became simpler and salaries lower. (It is believed that the recent string of Zenit failures can be tied to the loss of technicians in KB Yushnoye.)[121]

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[121]Leonard David, "U.S. Firms Ponder Dealings with Former Soviet Union", Space News, May 4-10, 1992.

IV. U.S./Russian Interactions in the SEI

The costs and benefits of using items of Russian space hardware in the SEI will depend to a large degree on the method of interaction between the United States and Russia. Items of Russian hardware that are not cost-effective for the U.S. to purchase for use in the SEI, for example, might be useful to the initiative if they were to be provided without charge by the Russians as part of a cooperative effort. In a similar vein, a piece of hardware unable to meet the SEI's technical requirements might serve as a valuable starting point for a joint U.S./Russian SEI hardware development program. A careful choice of methods of U.S./Russian cooperation, based on an understanding of the issues and actors involved, will be a crucial ingredient to the success of any effort to introduce Russian hardware into the SEI.

Issues Concerning the Use of Russian Space Hardware in the SEI

The first step in determining the best means of using Russian space hardware in the SEI is to examine the issues involved in such an endeavor. These include domestic policy issues, such as concerns about the impact of the use of Russian space hardware on the U.S. aerospace industry, on the rest of the space program, and on national prestige; and foreign policy issues, such as national security concerns, the situation within Russia, and the international reaction to U.S./Russian cooperation. Operational issues raised by the use of Russian hardware in the SEI must also be considered. These include the problems of dealing with the Russian government and industry, and the effects of cooperation on the overall cost and managerial complexity of the SEI.

The Effect on the U.S. Aerospace Industry

Use of Russian space hardware in the SEI could affect the U.S. aerospace industry. The primary concern is that such use might take business away from the U.S. aerospace industry while strengthening its Russian competition. On the other hand, cooperation with Russia could result in the transfer to U.S. industry of new technological capabilities, which would help to improve the position of U.S. firms vis-à-vis competitors from other nations. Cooperation with Russia might also potentially result in the U.S. moving forward with the SEI, providing the aerospace industry with years of lucrative government contracts.

Concern about the possible damage to U.S. industry from the use of Russian space technology in U.S. programs is valid. Distinctions must be drawn, though, between hardware (such as a lunar base) for which there is no foreseeable commercial market and hardware (such as a medium-lift launch vehicle) for which a commercial market already exists or might soon develop. A differentiation must be made between hardware that has already been developed by U.S. industry and hardware that has not yet been developed in the United States.

There is likely to be a greater problem from Russian hardware for which a commercial market already exists, or might soon develop, than from hardware for which there is no foreseeable commercial market. Government acquisition of commercially viable hardware, particularly in an industry (such as much of the space industry) where the products are highly expensive and sales are few, can result in a significant strengthening of the competitiveness of the hardware's producer, which, in turn, can eventually result in commercial gains to the producer that are far greater than the value of the government purchase. This effect is heightened for hardware items for which there is only an embryonic commercial market, as government support in such a case can often be critical to a company's survival.

Acquiring Russian hardware for which a U.S. equivalent already exists will be more of a problem than acquiring Russian hardware which has no equivalent in the United States. While the first case would result in direct losses to U.S. industry, acquiring Russian hardware for which there is no equivalent U.S. capability deprives U.S. industry only of the possibility of gaining a future development contract. Opposition to acquiring Russian hardware for which there is no equivalent U.S. capability is also likely to be muted because, while differences in costs between existing U.S. and Russian hardware are likely to be relatively small, the expense of developing entirely new hardware in the U.S. is likely to be far higher than the cost of purchasing existing Russian hardware.

One factor that might warm the response of the U.S. aerospace industry to the use of Russian hardware in the SEI is that such interaction could result in the transfer of advanced Russian technology to the United States. Such a transfer, particularly if the technology had some commercial application, could help increase the competitiveness of U.S. companies. There is another side to the issue; transfer of U.S. technology to Russian organizations could also occur. In this case, the aerospace industry would be averse to transferring technology that had commercial applications. The greater experience of the United States, and U.S. firms, in dealing in the international market, however, may insure that, at least at the beginning of any interaction, most technology transfer would be to the benefit of the United States.

Another reason that the use of Russian hardware in the SEI might not be strongly resisted by the U.S. aerospace industry is that such use could possibly be the critical act that convinces the nation (and Congress in particular) that the SEI is worth pursuing. (This issue is dealt with in greater detail in the next subsection.) As the U.S. aerospace industry sees the SEI as a potential source of significant long-term funding,[122] they may be prepared to overlook some of the possible disadvantages to the use of Russian hardware in it if they believe that such use is necessary to get Congress to begin providing that funding.

Concerns about the impact of the use of Russian space hardware on the U.S. aerospace industry will probably be one of the more important issues in deciding the means by which such hardware should be incorporated into the SEI. One group that will want to have a say in any such decision will be the aerospace lobby, which in the past has pressured the government to limit sales of foreign space hardware (though most of the government's decisions in this area have been based primarily on foreign policy and national security concerns.)[123] Probably more important than the aerospace lobby, though, would be the political fallout that the U.S. government would have to endure from supporting a plan which could be seen to be hurting U.S. firms. It seems likely that any plan that arguably hurt the aerospace industry would have to have significant cost or other benefits to be acceptable to the U.S. government.

The Impact on the Rest of the U.S. Space Program

The use of Russian hardware in the SEI could also have some effects on the rest of the U.S. space program. One possible effect is that such use might propel the SEI into a more prominent position relative to other space projects, perhaps affecting those projects. The use of Russian space hardware

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[122]Debra Polsky, "Aerospace Industry Antes Up", Space News, April 15-21, 1991.
[123]"Tell China and Russia the Rules", Editorial, Space News, July 20-26, 1992.

in the context of a large cooperative program, for example, might provide enough of a basic justification for the SEI to dramatically increase Congressional support for the initiative. Even lesser degrees of cooperation might convince Congress that the SEI would not be as prohibitively expensive as previously feared, leading to an increase in their support for it. If the SEI began to receive significant funding, this might (particularly in times of tight budgets) result in reductions in funding for other space projects, or in demands that the projects change in order to better support the goals of the SEI.

Use of Russian space hardware in the SEI might also result in an increase in the use of Russian space hardware elsewhere in the space program. There are already studies underway to determine whether a Soyuz capsule might be used as the space station's crew rescue vehicle,[124] and the use of the Energia vehicle to launch the space station has been discussed in Congress.[125] The broad use of Russian hardware in the SEI could open the door to the possibility of extensive use of Russian hardware throughout the rest of the U.S. space program. Extensive use of Russian hardware could result in the augmentation of some projects (for example, by using cheap Russian launch vehicles to launch space science satellites), and the redesign or cancellation of others (for example, the space station could be redesigned to be launched by the Energia).

The issue of the effect of the use of Russian space hardware in the SEI on the rest of the U.S. space program is likely to have only a small impact on any decision on whether such use should take place, or on how it should be

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124 Leonard David, "Soyuz Seen as Station Life Raft", Space News, April 27-May 3, 1992.
125 U.S. Congress Subcommittee on Space, "Bilateral Space Cooperation With the Former Soviet Union", Hearing, Washington: U.S. Government Printing Office, March 25, 1992.

managed. Reaction of supporters of various NASA projects will be muted because, first, there will be a lot of uncertainty about which programs will end up being affected, and second, the effect on the overall space program is likely to be heterogeneous, leading to a mixed reaction. The space station is the one project that may be powerful enough to exert a strong influence, and worried enough about its status to act despite uncertainty. Supporters of the space station would probably attempt to stop any use of Russian space hardware that they thought might imperil the project.

National Prestige

The use of Russian space hardware in the SEI could have a significant effect on the national and international prestige of the United States. No matter what the method of interaction involved, such activity would showcase the end of the Cold War and the new willingness of Russia and the U.S. to cooperate with each other. The overall form of the interaction, however, could either increase or decrease the amount and type of prestige gained.

The methods through which the U.S. and Russia might interact in the SEI will affect the prestige of the U.S. program in a not entirely obvious manner. For example, if the U.S. were to treat Russia as a mere hardware supplier, this might make the U.S. look powerful, especially compared to its former competitor, but it might also make the U.S. look like a "poor winner" of the Cold War, taking advantage of the troubles in the Soviet economy without giving anything back. On the other hand, if the U.S. were to cooperate closely with Russia on the SEI, it could lower the perception of the U.S. being far ahead of Russia in space, but it might also increase the perception that the U.S. is a "leader" in space.

The issue of the effect of using Russian space hardware in the SEI on national prestige may not play a significant role in any debate over if and how such interactions take place. The main reason for this is not because prestige is unimportant in the space program--it is one of the fundamental reasons the space program exists--but because many of the politicians and engineers involved in making decisions about the space program have become uncomfortable about making decisions based on prestige, rather than on technical or economic grounds. The undeniable symbolic value of U.S.-Russian cooperation in space, however, could force the prestige issue to be considered.

The Effect on U.S. National Security

There are three main national security-related issues associated with the use of Russian space hardware in the SEI. The first, already touched upon, is the need to maintain the military-related capabilities of the U.S. aerospace industry. The second, and historically most prominent, issue is the transfer of militarily useful technology between the United States and Russia. The third, and most controversial, issue is the effect of the use of Russian space hardware on that nation's military-industrial complex. These three issues are very likely to put some limits on any U.S./Russian interaction in the SEI.

The maintenance of U.S. space capabilities and the vitality of the U.S. space industry are national security issues because of the importance of space to U.S. intelligence and defense efforts. Though the preservation of existing capabilities is important to national security, it is unlikely that any capabilities that are currently being used for defense purposes will be lost due to the use of Russian hardware in the SEI. The more pertinent issue is the concern that the use of Russian hardware in the SEI might result in the loss of future capabilities due to the cancellation of some existing or planned U.S. development programs with potential military applications (such as the development of a U.S. heavy lift launch vehicle).

Notwithstanding that it has been used mainly as an excuse to prevent the Soviet Union and China from entering the commercial launch market, there is also a real national security-related issue in keeping advanced U.S. technology from falling into Russian hands. It is, however, an issue that is of less consequence since the breakup of the Soviet Union and the end of the Cold War. Now, even if Russia were to gain advanced military-related technology, it is not clear that they have either the desire or the funding to develop the technology into new military systems.

A perhaps more important side of the issue is that cooperation with the Russians in the SEI may lead to the transfer of advanced Russian military technologies to the United States. At least at present, though, the Russians seem quite willing to allow the U.S. military to directly purchase some of their advanced military technologies.[126,127] If this policy continues, the U.S. military will not need to use the SEI to gain new technologies, but if the Russians begin to close down the direct flow of their military technologies to the U.S. defense establishment, their participation in the SEI might become a useful source of technologies with military applications.

The third national security-related issue is the effect that the use of Russian space hardware in the SEI would have on the future of the Russian military-industrial complex. This is another issue with two sides; the use of

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[126] U.S. Congress Subcommittee on Space, "Bilateral Space Cooperation With the Former Soviet Union", Hearing, Washington: U.S. Government Printing Office, March 25, 1992.
[127] Andrew Lawler, "Defense Teams Leading Way to Soviet Store", Space News, September 23-29, 1991.

Russian space hardware in the SEI could conceivably either help to maintain Russian military capability or help to convert it to more peaceful uses. Current U.S. policy is to attempt to starve the Russian military-industrial complex; U.S. requests for acquisition of Soviet space technology currently have "the presumption of approval, unless the acquisition would in fact contribute to the maintenance of a threatening military capability."[128]

Support of the Russian space industry will have an effect on the nation's military-industrial complex because the Russian space program, even more so than the U.S. program, has many items of hardware with dual military and civil backgrounds and roles. For example, many Soviet launch vehicles are based upon ICBMs--some are produced in the same factories as ICBMs--and even the launch vehicles with no military heritage can be used to loft either civil or military payloads. Many spacecraft also have dual military and civil uses; two of the Salyut space stations, for example, were primarily used by the military.[129] SEI acquisition of either Russian hardware with dual military and civil uses or of hardware manufactured by organizations that also produce military systems could be seen as preserving Russian military capabilities.

But there are also a number of plausible reasons why the use of Russian space hardware in the SEI could aid in reducing the threat from the Soviet military-industrial complex. First, giving contracts to manufacture hardware for the SEI to factories that can produce either military or civil hardware may lead the factories to concentrate on their non-military production. Second, widespread U.S. purchase of Russian hardware might

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[128]Vincent Kiernan, "Russian Rockets: Threat or Economic Lifeline?", Space News, April 13-19, 1992.
[129]Brian Harvey, Race Into Space: the Soviet Space Program, Chichester: John Wiley & Sons, 1988, p.202.

aid in preventing sectors of the Russian space industry from completely collapsing, thus reducing the likelihood of unrest that might return hard-liners to power. Finally, the injection of Western cash into the Russian space program might help keep Soviet experts in some militarily relevant fields--such as nuclear power or rocket design--from looking for work in other countries.

National security-related issues could have a primary effect on decisions regarding the use of Russian space hardware in the SEI, due to the influence of the U.S. institutions involved. The most important of these issues will probably be the effect of such use on the Russian military-industrial complex. The final decision on how much Russian hardware should be used in the SEI may depend strongly on whether Russia is perceived to be continuing to dismantle its military, and on whether warm relations continue between the United States and Russia.

Concerns Within Russia

The Russian response to any U.S. efforts to use Russian space hardware in the SEI will probably be based on three major issues. Currently, the most important of these factors, from the Russian point of view, would probably be the economic costs and benefits of any participation in the SEI. The other two issues, however, the effect of participation in the SEI on Russia's national pride, and desire to not give away all of Russia's military technology, will tend to ameliorate any strictly economic approach to Russian participation in the SEI.

The economic costs and benefits of providing space hardware to the SEI will likely be an major factor in any Russian decision on participation in the initiative. Economic issues are currently of extreme importance in the

Russian space program; funding for space declined approximately 35% between 1988 and 1991, and the decline is continuing in 1992.[130,131] Foreign sales are sorely needed by the organizations involved in the Russian space program, both to preserve their work forces and to serve as signals to the government that they are producing valuable hardware and are thus worth maintaining. Foreign sales also provide an opportunity for the Russian government to point to actual benefits being produced by the nation's space program.

One counterbalance to the drive to market every item of Russian space hardware is the growing reaction against selling off the country's space assets at bargain-basement prices.[132,133] This reaction may have been sparked by a rumor that the United States wanted to buy the Mir space station in order to deprive Russia of its "trump card" in space;[134] it was augmented by the media backlash to the sale of the Topaz reactor. It is difficult to determine the strength of this "national pride", but it seems likely that it will result in some limits to what the Russians will sell (for example, they are unlikely to be willing to sell the working Mir space station); it may also result in an increase in the extremely low prices previously asked for Russian space hardware.

An important opportunity that is created by the remnants of Russian national pride in their space program is that it could lead the Russians to provide some hardware for the SEI on other than a strict cash basis. The hard

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[130]S. Zhukov et. al. "The Scientific-Technical Revolution and the Economy: Russia and Space", Pravitelstvennyy Vestnik, February 1992.

[131]Zhanna Shanurova, "Space is Again Asking for Money", Interview with Aleksandr Dunayev, Kuranty, March 6 1992.

[132]Peter B. deSelding, "Bargain Prices Build Russian Resentment", Space News, April 27-May 2, 1992.

[133]S. Brilev and St. Kutcher, "How We Helped the United States to Economize on the SDI Program", Komsomolskaya, April 15, 1992.

[134]Ravil Zaripov, "Lemons for the Funeral Repast, or 'Space Games' of the CIS", Moskovskiy Komsomolets, January 17, 1992.

currency obtained through the sale of an item of hardware would have to be gauged against the national prestige that could be gained from participation as a partner in an international space project. It is uncertain how strong this incentive is, as the Russian public is now generally unsupportive of the space program,[135] but it is a factor that may grow in relative importance if Russia's economic troubles decline.

The Russians may also be reluctant to sell items of space hardware that would allow other nations to acquire some of their unique military technologies. Although the Russian government permitted the sale of the militarily significant Topaz reactor, and reportedly has been willing to sell other military systems,[136] it seems likely that the future transfer of militarily significant hardware to the United States will not be without limits. If the Russian government strengthens its oversight of the space sector, it is possible that such military-related technology transfer may be further restricted.

International Issues

Wide-scale use of Russian space hardware in the Space Exploration Initiative is likely to have repercussions in other countries, particularly those with which the United States often participates in cooperative space endeavors. First, as has already been discussed, the use of Russian space hardware in the SEI could have an effect on the international perception of U.S. leadership in space. Second, the United States' space allies may want to join in any large-scale cooperative SEI program. Finally, countries

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[135]Andrey Tarasov, "Club 206: Into the International Space Year on the Fragments of the Space Program", Literaturnaya Gazeta, January 22, 1992.
[136]U.S. Congress Subcommittee on Space, "Bilateral Space Cooperation With the Former Soviet Union", Hearing, Washington: U.S. Government Printing Office, March 25, 1992, p. 107.

participating in international projects that might be indirectly affected by U.S/Russian cooperation in the SEI may be wary of such cooperation.

The U.S. is already involved in cooperative space activities with a large number of countries.[137] If the United States makes any broad cooperative agreement with Russia, some or all of these countries may want the U.S. to include them in the agreement. Such international cooperation could offer these countries a chance to use the space assets of the United States and Russia to augment their own capabilities, as well as allowing them to participate in some of the ongoing technology transfer, and perhaps to share in the prestige of participating in a visionary space effort. However, since the U.S. and Russian space programs dwarf all other space programs,[138] the roles of the other nations would probably be fairly minor. This could certainly change, though, over the long time frame of the SEI.

Probably more important to some countries is the effect of Russian participation in the SEI on cooperative projects that are already in existence, particularly the space station project. The current space station design includes one Japanese and one European experiment module (out of a total of four modules), as well as a Canadian robotic repair device. The nations participating in the space station program have already invested significant time and effort in developing their contributions, and see the space station as an important part of the future of their space programs.[139,140] For this reason,

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[137]For example, the Space Station and Spacelab projects involve Japan and the European Space Agency

[138]The next largest space program after the U.S. and Russian programs is probably the space program of the Ukraine, which basically consists of one major Soviet design bureau. The next after that, the program of the European Space Agency, is probably about a tenth the size of the U.S. and Russian programs.

[139]Kate Pound Dawson, "Japanese Request Moderate Gains in 1993 Space Budget", Space News, August 17-23, 1992.

[140]Peter B. de Selding, "ESA Circulates Streamlined Plan for Ministers' Review", Space News, June 15-21, 1992.

they, like other allies of the space station, may disapprove of any venture that might result in the cancellation of the project.

Dealing With the Russian Government and Industry

The difficulties of dealing with the Russian government and industry, particularly over the long-term, are likely to have a significant impact on any use of Russian space hardware in the SEI. The reason for this is that low hardware costs and high performance matter little if the hardware is held up in red tape, technical support is unavailable, or contracts are not honored. The two major issues in this area are the instability of the Russian government and space industry and the unfamiliarity of Russian space organizations with basic Western business practices.

As discussed in Chapter III, the stability of neither the Russian government nor the Russian space program is assured. One reason this instability is a major concern is because almost any use of Russian space hardware in the SEI will require long-term interactions with the hardware's producers. For example, an item of hardware that is acquired for long-term or repeated use, is going to be modified, or is going to be used as part of a hardware development program, will require extended technical support from the people within Russia who know the hardware's subsystems, history, and quirks. The availability of this technical support will depend on both the continued stability of the organization that provides the support, and the government policy that allows the organization to provide the support.

The other major problem with the instability in Russia is that it makes it dangerous for the U.S. to plan for the future use of Russian hardware. This is a particularly serious danger for large hardware items, which can have decade-long development times, and for hardware that is required for missions which are essential for the continuation of the initiative. For example, if the U.S. planned to use the Energia heavy lift vehicle to put a base on the Moon in 2004, and then was prevented from doing so by events within Russia in 2003, the entire schedule of the SEI could be delayed for years as the U.S. developed its own heavy lift vehicle.

In addition to the long-term problem of the instability of the Russian space program, there is also a short term problem that may hamper some methods of using Russian space hardware in the SEI. This problem is that the Russian space industry is currently very unfamiliar with basic Western business practices.[141] For example, Russian firms have been reluctant to provide Western firms with the amount of technical data that is needed to assess the viability of possible cooperative efforts. In addition they seem to have little understanding of the degree of control which Western system prime contractors or integrators have over the technical details of the subcontractors' work.[142] Finally, they are unfamiliar with Western contract law, as was evidenced when Glavkosmos, the Soviet marketing agency, signed simultaneous exclusive contracts for microgravity experimentation with a number of European organizations.[143]

The Russian space industry's inexperience with Western business practices will have an effect on some types of interactions with the United States, at least until the Russians learn Western business practices. First, U.S. industry will be wary about dealing with the Russian space industry unless they receive some assurance that the Russians will abide by any contracts they

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[141] Leonard David, "U.S. Firms Ponder Dealings with Former Soviet Union", Space News, May 4-10, 1992.
[142] Edward Crawley and Jim Rymarcsuk, "US-Soviet Cooperation in Space", Space Policy, February 1992.
[143] Peter B. de Selding, "Firms Question Exclusivity of Soviet Contracts", Space News, July 8-14, 1991.

sign. Second, problems may arise even after the contracts are signed, as U.S. primary contractors and Russian subcontractors argue over their respective responsibilities. While contact with U.S. companies will help Russian firms learn Western business practices, the U.S. might encounter less problems if it were to deal with the firms through more traditional channels, such as through the Russian government. (On the other hand, the current situation in Russia is such that agreements for international hardware sales made between private organizations are much simpler and less time-consuming than intergovernmental agreements.[144])

Concerns About Cost

One of the most crucial issues in the use of Russian hardware in the SEI is how such use will affect the cost of the initiative. The SEI's greatest stumbling block has always been its huge cost, and one of the primary motives for using Russian space hardware in it would be to reduce that cost. The effect of the use of Russian space hardware on the cost of the SEI will depend on the (previously discussed) impact on the U.S. aerospace industry, the cost of the Russian hardware (as compared to the cost of the alternative), the cost of integration, and the willingness of the Russian government to provide the hardware at a reduced cost.

Direct purchases of items of Russian space hardware may not provide as much cost savings as the prices presently being advertised might indicate. The factors that have been causing Russian organizations to offer to sell their hardware at bargain prices over the last couple of years (the reduction in overall space funding, combined with unfavorable exchange rates and a lack

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[144] Vincent Kiernan, "Russians Put Strings on Reactor Purchase", Space News, May 4-10, 1992.

of knowledge of the real costs of producing hardware) are unlikely to continue over the time-frame of the SEI (where the first launch may not come until the end of the 1990s). The effect may be that the extremely low prices that have been quoted for various items of Russian space hardware will begin to rise in the near future. On the other hand, many items of Russian hardware are going to remain cheaper than their Western alternatives due to their simplicity, the years of experience the Russians have in producing them, and the low cost of skilled Russian labor.

In addition to the direct cost of purchase, there is also a 'hidden' cost to the use of Russian space hardware in the SEI--the cost of integrating the hardware into the overall U.S. space program. The integration costs can be a major factor in the overall cost of any hardware. Integration of the Soyuz spacecraft with the U.S. space station, for example, would require modification of the docking equipment, changing the cabin's internal pressure, and adding an additional seat, alterations that could end up being more costly than the actual purchase of the Soyuz capsule.[145]

Costs of integration of Russian hardware into the SEI will depend on how closely the two nation's hardware is linked. For example, launch of a Russian robotic probe on a Russian launch vehicle would not require any additional integration. Slightly more costly would be modifications to the design of new U.S. hardware so that it could be used with Russian hardware, such as a lunar lander that could dock with a Russian space station module. Very high integration costs are likely to be incurred when existing hardware must be modified to work with the hardware of the other nation. For example, the Apollo-Soyuz mission required the development of an entirely

[145]Leonard David, "Soyuz, Shuttle Join Stable of Rescue Vehicle Contenders", Space News, February 10-16, 1992.

new docking system and the development of an emergency pressurization system for the Soyuz capsule, among other changes.[146]

The final, and maybe most important, issue affecting the cost of using Russian hardware in the SEI is the willingness of the Russian government to fund Russian participation in the SEI. Although the Gorbachev government offered to mount a bilateral Mars mission with the U.S., as an alternative to the Strategic Defense Initiative[147], it is not clear if the present or future Russian government would do such a thing; such a decision would depend upon the offer to participate made to them by the U.S., the economic and political situation, the economic costs and benefits, and the perceived benefits to national prestige.

Management of the SEI

A final issue is the effect that the use of Russian space hardware in the SEI would have on the management of the initiative. No matter how Russian hardware is introduced into the SEI, it will increase the managerial complexity and loosen the managerial control of the initiative. The primary cause will be the introduction of Russian organizations into the hierarchy, organizations that are not subject to the same rules as the U.S. organizations involved in the initiative. The seriousness of this problem will depend on the previously discussed difficulty of dealing with the Russians and on the level of Russian participation in the SEI. For example, the addition of a few Russian subcontractors will not pose nearly as large a problem as the development of a joint U.S./Russian lunar base would.

[146]Edward and Linda Ezell, The Partnership: A History of the Apollo-Soyuz Test Project, Washington DC: NASA, 1978, p. 210.
[147]V. Glushko, et. al., "Fantasy on the Drawing Board: The Road to Mars", Pravda, May 24, 1988.

Another possible management problem is that both the U.S. and Russia might have difficulties in participating in any cooperative programs in which they do not have the lead role.[148] The U.S. traditionally insisted that it have a leadership position in all of its major cooperative space projects (with the exception of Apollo-Soyuz), as did the Soviet Union. This may not be a significant problem for interactions which only involve purchases of Russian hardware, but it could complicate the initiation of any joint programs.

Methods of U.S./Russian Interaction in the SEI

The use of Russian space hardware in the SEI can be handled through a number of different means, ranging from the direct purchase of Russian hardware for use in U.S. missions to fully cooperative programs. It is not necessary to use one type of interaction over the whole SEI; instead, different methods might be used for different kinds of hardware. The optimum means of cooperation for each type of hardware will depend on the issues discussed in the previous section, as well as on factors particular to each method of cooperation.

There are six different basic methods that could be used to incorporate Russian hardware into the SEI. Other possible cooperative methods (such as making the U.S. and Russia equal partners in the SEI) do exist, of course, but the six discussed are the ones that are probably the most feasible considering economic and political realities. The six methods are:

1) Scientific cooperation

2) U.S. purchase of Russian technology to aid in U.S. hardware development

[148]Crawley, Edward and Rymarcsuk, Jim, "US-Soviet Cooperation in Space", Space Policy, February 1992.

3) Use of Russian hardware by U.S. industry

4) U.S. purchase of Russian space hardware

5) U.S. -led endeavor with close Russian participation

6) U.S. -led endeavor with separate Russian participation

Scientific Cooperation

Scientific cooperation is defined here as cooperation between U.S. and Russian scientists that generally does not involve either the exchange of money or the development of hardware other than scientific instruments. This type of cooperation could include such activities as the use of one nation's scientific instruments on the spacecraft of the other nation, the development of joint experimental protocols, and the sharing of scientific data. Large scale activities such as the joint development of a lunar orbiter, or of a nuclear thermal rocket are not considered scientific cooperation.

The long and successful history of international scientific cooperation in space will make it easier for such cooperation to occur in the SEI. Both nations have significant experience in this type of cooperative endeavor in space, from programs like the Phobos spacecraft, which had instruments from thirteen nations,[149] to the ongoing cooperation between the United States and Russia in sharing life sciences data.[150] The scientific community has become so used to international scientific cooperation that they would probably protest fairly strongly if such cooperation did not take place in the SEI.

Few major problems are likely to arise over U.S/Russian scientific cooperation in the SEI. Such cooperation would not significantly effect the

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[149]R.Z. Sagdeev & A.V. Zakharov, "Brief History of the Phobos Mission", Nature, October 19, 1989.

[150]Office of Technology Assessment, Exploring the Moon and Mars, Washington D.C.: U.S. Government Printing Office, July 1991.

U.S. aerospace industry, U.S. national security, other programs inside NASA, or other international cooperative projects. It also seems likely that such cooperation would not meet any significant resistance from the Russian government or industry. Finally, because of the means by which scientific cooperation occurs, it would not add to the managerial complexity of the SEI, nor be hampered by the inexperience of most Russian organizations in dealing with the West. On the positive side, U.S/Russian scientific cooperation could help produce better scientific results without significantly increasing cost and, in a small way, could increase national prestige for both nations.

The only real concern about this type of cooperation is that there could be problems if, due to the instability within Russia, funding for Russian instruments that were to be used on a U.S. spacecraft was lost part way through the project. This would not be a very large problem, though, as, depending on the criticality of the instrument, it could either be left off, or the U.S. could provide the (relatively small) amount of funding necessary to complete the project.

U.S. Purchase of Russian Technology to Aid in U.S. Hardware Development

In this mode of cooperative activity, the U.S. would purchase an item of Russian hardware to serve as the starting point for the development of new hardware for use in the SEI. An example of this type of interaction might be if the U.S. were to use the recently purchased Topaz thermionic reactor to learn how to build a large thermionic reactor that would be used to power a lunar base. This type of development could be carried out as a strictly U.S. program or as a bilateral effort with the developers of the original Russian hardware.

From the U.S. point of view, this type of program has a lot of advantages. First, it directly transfers advanced technologies to the United States, to the possible benefit of the U.S. military and aerospace industry. Second, it can result in significant cost savings by taking the place of years of preliminary technology development. The only likely domestic problems such activity might cause would be if it were to threaten an ongoing technology development program. (The purchase of the Topaz reactor has already set off a reaction by threatening the U.S. SP-100 reactor program.)[151]

The largest obstacle to this type of interaction might come if Russia, for reasons of prestige or national security, declined to sell their hardware to the United States for such use. This problem could probably be avoided if there was Russian participation in the technology development program, or if it the development was performed in the context of wide U.S./Russian cooperation in the SEI. Russian participation might reduce some of the technology transfer-related benefits, and possibly increase the management complexity of the activity, but it would also probably significantly speed up the new hardware development.

Use of Russian Hardware by U.S. Industry

In this mode of interaction, the U.S. would encourage its industries to use Russian hardware in their proposals for SEI contracts. This could probably be done simply by easing restrictions on such use, and letting U.S. firms know that they would not be penalized in contract awards for having Russian subcontractors. U.S. industries would be left to decide whether they wanted to directly purchase the hardware from Russian industries, use the

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[151] Andrew Lawler, "House Panel Members Attack Topaz Purchase", Space News, February 3-9, 1992.

Russian companies as subcontractors, or perhaps use other methods of interaction. An example of how this might work in the SEI would be if NASA were to issue contracts for a lunar orbital base and a U.S. contractor were to subcontract with KB Salyut to develop a modified Salyut-type module for this base. (This approach is being considered in the current study of whether a Soyuz capsule might be used as a crew escape vehicle for the U.S. space station.[152])

This type of cooperation has a number of advantages. First, it would allow industry to find the most efficient manner in which to use Russian space hardware in the SEI, which would probably result in significant cost savings. Second, by interacting with U.S. industry, the Soviet enterprises involved will learn Western business practices, which might in some small way help ease the Russian transition to a market economy. Aerospace companies in the U.S. have also generally been in favor of this kind of approach to using Russian space hardware,[153] probably because it ensures that they will have a chance to be involved in hardware development, and perhaps also because of the potential for technology transfer.

There are some disadvantages to this type of cooperation, though. The largest will probably be the difficulty the companies will have dealing with the Russian government and industry, especially because U.S. industries can not exert as much political pressure as could be exercised by the U.S. government. This problem could be eased, though, if NASA were to work closely with the Russian government to solve any major problems that were encountered. The other main concern is that this type of interaction might

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[152]Andrew Lawler, "Senate Panel Opposes Broker for Soyuz Deal", Space News, August 24-30, 1992.

[153]U.S. Congress Subcommittee on Space, "Bilateral Space Cooperation With the Former Soviet Union", Hearing, Washington: U.S. Government Printing Office, March 25, 1992, p.49.

cause a lot of trouble because the U.S. companies involved would probably be very concerned with the effect of U.S./Russian cooperation on their other space business, and might not be particularly concerned with other issues, such as national prestige and national security issues. This could quite conceivably result in a great deal of controversy over their proposals for use of Russian hardware in the SEI.

U.S. Purchase of Russian Space Hardware

In this type of interaction, the U.S. (through NASA) would purchase Russian hardware, either through intergovernmental agreements or through direct acquisition from the Russian hardware producers. For example, NASA might purchase two Energia rockets from NPO Energia to use to launch a Mars transfer vehicle. This type of cooperation might also include some additional contracting with either Russian or U.S. companies to integrate the hardware with U.S. SEI hardware.

This simple type of interaction has fewer advantages than, for example, a wide-ranging cooperative program, but it also has few disadvantages. On the positive side, direct purchases of Russian hardware would result in cost savings over the development of equivalent U.S. hardware and would not add greatly to the complexity of the initiative's management. In addition, NASA, as a government organization, might have less trouble in dealing with the Russians than U.S. industry would have. The only real problems with this type of arrangement are, first, that the SEI could be vulnerable to the instability inside Russia if NASA planned to use Russian hardware for critical SEI tasks and, second, that the U.S. aerospace industry might not be very supportive of this type of interaction because they would be losing possible development funding but gaining very little.

U.S.-led Endeavor With Close Russian Participation

In this type of interaction, the United States would make the SEI a cooperative venture and ask the Russians (probably in addition to the European Space Agency and Japan) to participate as junior partners. As in the Space Station project, the international partners would contribute items of hardware and the U.S. would provide the balance of the hardware and the broad systems engineering. An example of Russian contributions under this method might be the development of a nuclear power system for a lunar base, or the provision of Soyuz modules as emergency lunar return vehicles.

There are a number of advantages to this type of approach. First, there would be very large cost-savings gained by having the Russians pay for their own part of the initiative. This type of cooperation would also be very high-profile, and thus could lead to greater support for the SEI. In addition, Russian contributions could probably be restricted to areas where the U.S. has no equivalent hardware, and would not be competing for U.S. funds, so there would be little protest from the U.S. aerospace industry. Finally, the close cooperation could lead to significant amounts of technology transfer (though the transfer would probably be in both directions.)

There are, however, numerous possible difficulties with this type of approach. One large problem is that the initiative would become hostage to the political climate in Russia; changes in the Russian participation in the SEI could result in the delay or even the cancellation of the initiative. Another major problem is that management complexity of such a program would be very high. Perhaps the greatest problem is that for this scheme to work, the Russians would have to be willing to contribute their own hardware, free of charge. Convincing them to do this might require that the U.S. publicly play up the importance of the Russian contribution.

U.S.-led Endeavor With Separate Russian Participation

This type of interaction would differ from the previous method in that the Russian segment of the SEI would be kept separate from the U.S. part, and, wherever possible, would not extend to elements on the 'critical path' of the SEI (i.e. parts of the SEI that, if delayed or cancelled would result in the delay of the entire initiative). For example, the U.S. could ask the Russians to participate in the SEI by sending robotic rovers to the Moon and orbiters to Mars to prepare for later human missions. This type of cooperation has been used successfully before, notably in the international effort to study Halley's Comet,[154] **and was recommended by U.S. scientists for the robotic exploration of Mars.**[155]

This type of cooperation has some of the advantages of the previous method, but avoids almost all of its disadvantages. While maintaining significant cost savings, this method avoids the problems associated with the instability of the Russian space program, and would require much less managerial complexity. The problem in convincing the Russians to pay for their own missions would remain, but both the costs to the Russians and the prestige gained from participating in the SEI would be lessened. Finally, unlike the previous method of cooperation, this type of cooperation would result in very little technology transfer in either direction.

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[154] J. Kelly Beatty and Andrew Chaikin, eds., The New Solar System, Cambridge, MA: Sky Publishing Corporation, 1990, pp. 208-216.
[155] Andrew Lawler, "Panel: U.S. - Soviet Mars Work Should Not Merge", Space News, April 23-29, 1990.

V. Basic Mechanics of Space Exploration

It is necessary to understand the physical parameters of the SEI in order to assess possible exploration plans and the hardware that will be required to implement them. This understanding requires specification of the locations that might be visited by SEI missions, an appreciation of the basic celestial mechanics involved in travelling between the Earth and other points in the inner solar system, and a sense of some of the operational concerns of SEI missions, including the difficulties of conducting lengthy space missions involving human presence.

Locations

To reach the the Moon and Mars, the SEI's primary destinations, spacecraft must first pass through the near-Earth area. The near-Earth area can be defined as ranging from the altitude at which short-term atmospheric drag becomes negligible and spacecraft are able to orbit the Earth (about 150 kilometers above the surface of the planet) to about a million kilometers from the Earth (three times the distance to the Moon), where the gravitational attraction of the Sun becomes dominant. The characteristics of different regions within the near-Earth area vary widely.

Low Earth Orbit (LEO) is the area from about 150 km to 1000 km above the planet. Humans have over 20 man-years of experience in LEO, and robotic spacecraft far more than that. Above LEO are the Van Allen belts, tori of charged particles which reach to from about 1,000 to 20,000 km above the Earth. Numerous robotic satellites routinely travel through the Van Allen belts, but the Apollo missions are the only piloted spacecraft ever to have passed through them. The most notable area above the Van Allen belts is geosynchronous orbit, 35,000 kilometers above the Earth. At this altitude, satellites in orbit have the same period as the Earth, and those in 0° inclination orbits remain fixed above one point on the Earth. Over the last three decades, numerous robotic satellites (but no humans) have been placed in geosynchronous orbit.

The Lagrange points of the Earth-Moon and Earth-Sun system are areas in the vicinity of Earth with particular qualities that may make them useful to the exploration effort. Lagrange points are locations where the gravitational attractions of two bodies are balanced; a spacecraft at one of these points will not be drawn towards either of the bodies. There are five Lagrange points (known as L_1 through L_5) in the Earth-Moon system; these points orbit the Earth with the same period as the Moon. Figure V-1 illustrates the location of the Earth-Moon Lagrange points. (The Sun-Earth system also has five Lagrange points in the same relative positions.)

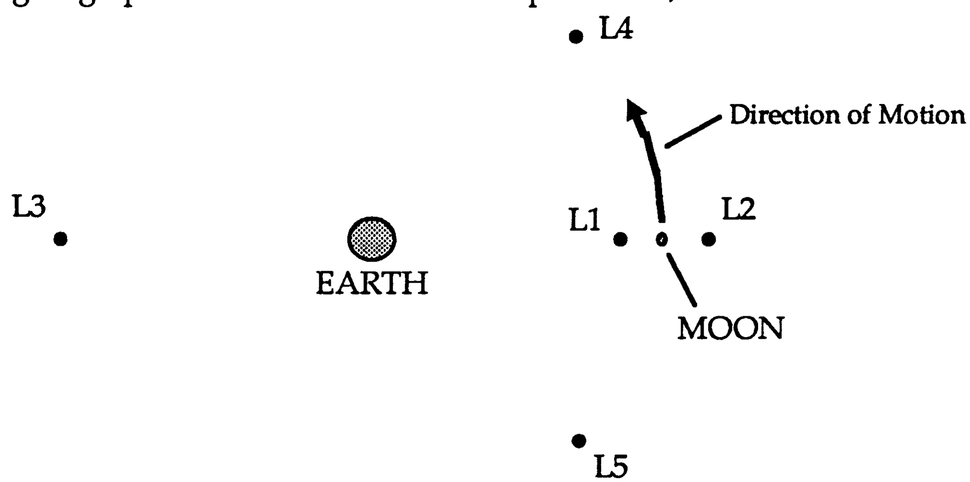

Figure V-1: Location of Lagrange Points in Earth-Moon System

Though not all of the Lagrange points are stable (i.e. a spacecraft that begins to drift away from them will continue to drift away), stable "halo" orbits around the points can be maintained with minimal energy expenditure. The

Lagrange points can be useful to exploration missions as "resting points" that are not tightly bound to a planet's gravity. The utility of the Lagrange points was shown by the ISEE-3 spacecraft, which, after completing its mission in a halo orbit around the Sun-Earth L_1 point, used very little fuel to maneuver into a position where it could measure the Earth's geomagnetic tail and then rendezvous with comet Giacobini-Zinner.[156]

The Moon orbits the Earth at a distance of 384,000 km, about ten times further out than the orbit of geosynchronous communications satellites and a thousand times higher than a typical space shuttle orbit. The Moon's orbit is inclined 5° to the plane of the ecliptic, so the inclination of its orbit to Earth's equator varies (over an 18.5 year period) from 18° to 28°. The Moon is about one quarter the diameter of the Earth, with about one eightieth the Earth's mass, and a surface gravity approximately a sixth that of the Earth. It has no general atmosphere or magnetic field; the lunar surface is exposed directly to the solar wind and the interplanetary radiation environment. The Moon revolves around the Earth with a period of 27.3 days, with one side always facing the Earth. Because of this, the lunar days and nights are approximately 14 Earth days long. Lunar temperatures vary from 393 K (120 °C) in the daylight to 153 K (-150 °C) in the dark.[157] The U.S. Apollo and Soviet Luna missions in the late 1960s and early 1970s proved the feasibility of landing machines and men on the Moon and returning them safely to Earth.

Mars orbits the Sun with a period of 687 days. Its orbit is slightly elliptical, so its distance from the Sun varies about 20% over a Martian year. Due to this variation, and the different orbital periods of the Earth and Mars,

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[156]Paul W. Keaton, "A Moon/Mars Base Transportation Depot", Lunar Bases and Space Activities of the 21st Century, Houston: Lunar and Planetary Institute, 1985, p.144.

[157]T.D. Lin, "Concrete for Lunar Base Construction", Lunar Bases and Space Activities of the 21st Century, Houston: Lunar and Planetary Institute, 1985, p.144.

the distance between the two planets can vary from about 56 million to 400 million km. Mars is about half the diameter of the Earth, with about a tenth of the Earth's mass, a surface gravity about a third that of the Earth, and a magnetic field 5000 times weaker than the Earth's. The Martian atmosphere is primarily composed of carbon dioxide (CO_2); its density varies by up to 20% over the Martian year (as the CO_2 condenses at the winter pole). The average atmospheric pressure at the surface is about .007 Earth atmospheres, and the average surface temperature about 218 K (-55 °C). Mars experiences frequent dust storms; at certain times these storms can grow to global proportions. Mars rotates with a period of 24.6 hours, giving it days and nights of about the same length as we are used to on Earth. On Mars however, the sunlight is only 43% as intense as it is on the Earth, due to the planet's greater distance from the Sun. Mars has been visited by the U.S. Mariner orbiter and Viking landers, and the Soviet Mars and Phobos spacecraft. No piloted or round-trip robotic spacecraft have yet been sent to Mars.

Mechanics of Space Travel

To reach the Moon and Mars, the piloted and robotic spacecraft of the SEI will have to escape the gravitational pull of the Earth, travel some distance through space, and then achieve the correct velocity to either orbit or land on their destination. Many missions will then require that the spacecraft return to Earth. New methods of achieving these ends with minimum energy use and travel time are continually being developed, but all are refinements or combinations of a few basic techniques dictated by the laws of celestial mechanics. These laws and techniques constrain the set of possible missions for the SEI and drive the technology requirements for those missions.

The first step in travelling to the Moon or Mars is to rise above the Earth's atmosphere with enough velocity to not fall back. Achieving this will get a spacecraft into orbit (higher velocities will allow the spacecraft to escape the Earth's gravity entirely). This is the part of the journey that requires the most energy expenditure in the least time. Due to the strong gravitational attraction of the Earth, travelling the few hundred kilometers from the surface to LEO requires more ΔV (change in velocity) than is required for travelling the millions of kilometers from LEO to the surface of Mars. Travel times to orbit are short as it is inefficient to travel slowly up through the Earth's strong gravitational field; usually acceleration is high and LEO is reached in about 10 minutes.

LEO provides a convenient "resting point" for spacecraft, as they need minimal energy to maintain their orbit, are still protected from radiation by the Earth's magnetic field, and maintain a high velocity (which is important for transfers beyond Earth orbit). The theoretical velocity required to reach a circular orbit at the same inclination as the launch site is:

$$V_{\text{to orbit}} = \sqrt{\frac{2GM}{R_{planet}} - \frac{GM}{R_{orbit}}}$$

where G is the gravitational constant, M is the mass of the planet, R_{planet} is the radius of the planet. and R_{orbit} is the distance from the planet's center of mass to the spacecraft. The rotation of the planet, however, gives launches in the direction of the planet's rotation an initial velocity of

$$V_{init} = \left(\frac{2\pi R_{planet}}{T_{planet}}\right)\left(\cos \varnothing\right)$$

where T_{planet} is the period of the planet's rotation and Ø is the latitude of the launch site. Finally, there are losses due to gravity and drag on the launch vehicle. (For a typical launch from Earth, ΔV losses due to atmospheric drag and gravity are about 1500 m/s.) The total ΔV required to reach a circular orbit at the same inclination as the launch site is thus:

$$\Delta V_{\text{to orbit}} = \sqrt{\frac{2GM}{R_{\text{planet}}} - \frac{GM}{R_{\text{orbit}}}} - V_{\text{init}} + \Delta V_{\text{loss}}$$

For example, launch from the Kennedy Space Center into a 28.5° inclination orbit with an altitude of 500 km requires a ΔV of about 9.3 km/s.

Orbital velocity decreases with altitude for both circular and elliptical orbits. The velocity required to maintain a circular orbit about a planet is

$$V_{\text{circ. orbit}} = \sqrt{\frac{GM}{R_{\text{orbit}}}}$$

For example, a spacecraft in a 500 km circular orbit has a velocity of about 7.1 km/s while a spacecraft in geosynchronous orbit has a velocity of 3 km/s. The velocity of a spacecraft in an elliptical orbit varies with the location of the spacecraft in the orbit as

$$V_{\text{ellip. orbit}} = \sqrt{\left(\frac{2GM}{D} - \frac{GM}{A_{\text{orbit}}}\right)}$$

where D is the distance from the planet's center of mass to the spacecraft and A_{orbit} is the semi-major axis of the elliptical orbit. Elliptical orbits can be useful for transferring between orbits, for capture from interplanetary trajectories, and for other specialized applications.

For many missions, it is necessary for spacecraft to conduct plane change maneuvers to adjust the inclination of their orbits. (The inclination of an orbit is the angle between its orbit plane and the Earth's equator.) When a payload is launched, the minimum energy orbit for it to enter is one with the same inclination as the launch site. For example, payloads launched from the Kennedy Space Center, at 28.5° N latitude, are usually launched into an orbit inclined at 28.5°. While it is possible to launch into an orbit with a higher inclination than the latitude of the launch site, direct launch into a lower inclination orbit is not possible.

Spacecraft can also change inclination of their orbits after the spacecraft has reached orbit. Though this maneuver generally takes much more energy than directly launching into the desired inclination, it is necessary when the desired final orbit inclination is lower than the latitude of the launch site. The energy cost for a change in inclination (a plane change) in orbit is

$$\Delta V = 2V_{orbit}\sin\left(\frac{\Omega}{2}\right)$$

where V_{orbit} is the initial orbital velocity and Ω is the magnitude of the angle between the two orbital planes. For example, the ΔV for transfer from a 500 km altitude orbit at 28.5° to a 500 km altitude at 45.6° is 2.26 km/s. As can be seen, plane changes require less ΔV at higher altitudes, where the spacecraft's velocity is lower. In fact, for plane changes greater than 50°, it takes less energy to completely escape the Earth's gravitational attraction and then return to the desired orbit inclination (though it takes much more time). The energy required for this maneuver is at least

$$\Delta V = 2V_{orbit}\left(\sqrt{2} - 1\right)$$

For missions beyond Earth orbit, spacecraft must "escape" the Earth's gravitational attraction. The minimum escape velocity from a circular orbit is

$$V_{escape} = \sqrt{2}\, V_{circ.\ orbit}$$

so the ΔV for the maneuver is

$$\Delta V_{escape\ from\ orbit} = \left(\sqrt{2}-1\right)\sqrt{\frac{GM}{R_{orbit}}}$$

though more velocity may be needed for certain types of transfer maneuvers. If the escape maneuver is performed directly from the planet's surface, the ΔV required is

$$\Delta V_{escape\ from\ surface} = \sqrt{\frac{2GM}{R_{planet}}}$$

which is slightly less than the ΔV required to enter an orbit and then reach escape velocity from there. The major advantage of using a "parking orbit", though, is that it is very difficult (due to weather, complex launch vehicles, etc.) to launch directly from Earth with the precise timing needed to enter a minimum-energy interplanetary trajectory. A spacecraft in orbit, however, can just wait until its orbit plane lines up with the correct trajectory.

Careful planning of a spacecraft's trajectory can minimize the ΔV required for travel between various points of interest beyond Earth's orbit. One way of doing this is by scheduling travel for times when the Earth, the spacecraft's orbit, and the target are aligned so that minimal ΔV is needed. Performing the appropriate orbital transfer maneuver is also important in minimizing required ΔV. Finally, trajectories can pass close by large bodies to gain extra ΔV.

The Earth and the Moon are always at the same distance from each other, so the major scheduling problem to minimize ΔV for travel between them is in lining up the plane of the spacecraft's orbit with the plane of the Moon's orbit. The inclination of the Moon's orbit varies from 18° to 28°, so the plane of any Earth orbit with an inclination greater than 28° will eventually pass through the plane of the Moon's orbit. An orbit around a planet precesses at a rate of

$$\Omega = 1.5\,(J_2)\,\sqrt{GM}\,(R_{planet})^2\,(R_{orbit})^{-3.5}\,(\cos i)$$

where Ω is the retrograde precession of the orbit plane in degrees/day, J_2 is a constant based on the oblateness of the planet, and i is the orbit inclination.[158] A minimum energy transfer becomes possible when the orbit plane (precessing retrograde at a few degrees a day, lines up with the Moon, which is

[158]Gordon R. Woodcock, "Mission and Operations Modes for Lunar Basing", Lunar Bases and Space Activities of the 21st Century, Houston: Lunar and Planetary Institute, 1985.

precessing in a posigrade direction at a rate of about 13.2° a day. Such a situation occurs every

$$\frac{180°}{13.2 + \Omega} \text{ days}$$

Since low inclination orbits precess faster than high inclination orbits and low altitude orbits precess faster than high altitude orbits, low altitude and low inclination orbits will have more opportunities for a minimum energy lunar transfer. As an example, a 300 km, 28.5° orbit will have an opportunity for an in-plane transfer to the Moon every 8.9 days, while a 1000 km, 60° orbit will have one every 11.1 days.

An additional factor that must be considered is the spacecraft's destination on or around the Moon. Again, the timing of the transfer from Earth is important in avoiding substantial additional ΔV expenditures. The spacecraft's velocity relative to the Moon is a vector sum of its velocity relative to the Earth and the Moon's orbital velocity; changes in the velocity vector relative to the Moon will allow orbits or destinations of any given inclination to be entered without the need for plane-change maneuvers. Again, to allow minimum-energy transfers, the precession of the spacecraft's orbit plane around Earth must be synchronized with the precession of the Moon. Although Earth orbits exist where all the planes line up in simultaneously on a regular basis, some additional ΔV must often be expended.

Minimum energy trajectories for interplanetary transfers also become available when the orbit planes line up, but since (unlike the Moon) the planets do not precess rapidly around the Earth, the times when the spacecraft's orbit plane lines up with the plane of the planet's orbit come less often. For example, a 300 km, 28.5° orbit crosses the plane of Mars' orbit every

25 days and a 1000 km, 60° orbit crosses it every 60 days. This is particularly a problem if a spacecraft travelling to Mars and back is supposed to end its round trip in the same orbit that it left from (to rendezvous with a space station, perhaps.)

The major problem with entering interplanetary trajectories is not the problem of lining up the orbit plane with the plane of the target planet's orbit, however, but rather in timing the missions so that the two planets are at the best relative positions to minimize total ΔV requirements. The period between times when two planets are in the same relative positions to each other is

$$T = \frac{1}{\left| \frac{1}{T_1} - \frac{1}{T_2} \right|}$$

where T_1 and T_2 are the orbital periods of the two planets. The Earth and Mars, for example, are in about the same relative positions to each other only every 26 months. (The eccentricity of Mars' orbit results in exact configurations being repeated only every 15 years.)[159]

Further complicating the timing of interplanetary travel is the necessity in many missions for the spacecraft to eventually return to the Earth. A returning spacecraft must be sure that the Earth will be in the correct position for the transfer home. The time a spacecraft must wait for a minimum energy return trajectory is

$$t_{wait} = \frac{4\pi \left(\frac{t_{trip}}{T_1} \right)}{\left| \frac{1}{T_1} - \frac{1}{T_2} \right|}$$

where t_{trip} is the travel time between the two planets. The total time for a minimum-energy trip between two planets is equal to

[159]Synthesis Group on America's Space Exploration Initiative, America at the Threshold: America's Space Exploration Initiative, U.S. Government Printing Office, Washington, 1991.

$$t_{total} = t_{wait} + 2(t_{trip})$$

For an Earth-Mars trip, a minimum energy t_{trip} might be 260 days, so t_{wait} is 454.3 days, so the minimum energy total trip time is 975 days. Using more energy will widen the available launch windows.

Figure V-2, a "porkchop" curve for the 1990 launch windows for Mars, gives an idea of how the trip time, ΔV requirements, and launch dates are interrelated.[160] In this figure, the diagonal lines are trip times, and the curves represent the C^3 (which is ΔV squared) required. For example, to make a 100-day trip, a ΔV of about 7 km/s is required (with a launch window of about 10 days), while a 200 day trip can be performed with a ΔV expenditure of about 4 km/s. The two sets of curves (Type I and Type II) are for different orientations of the Earth and Mars; in general the minimum ΔV values can be found in Type II (long-duration) missions.

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[160]James R. Stuart and Randall E. Coffey, "Analysis of Delivery Capabilities to Low Mars Orbits Applying Current Technology Launch/Retro Propulsion Systems", The Case for Mars II, San Diego: Univelt Inc., 1985, p. 396.

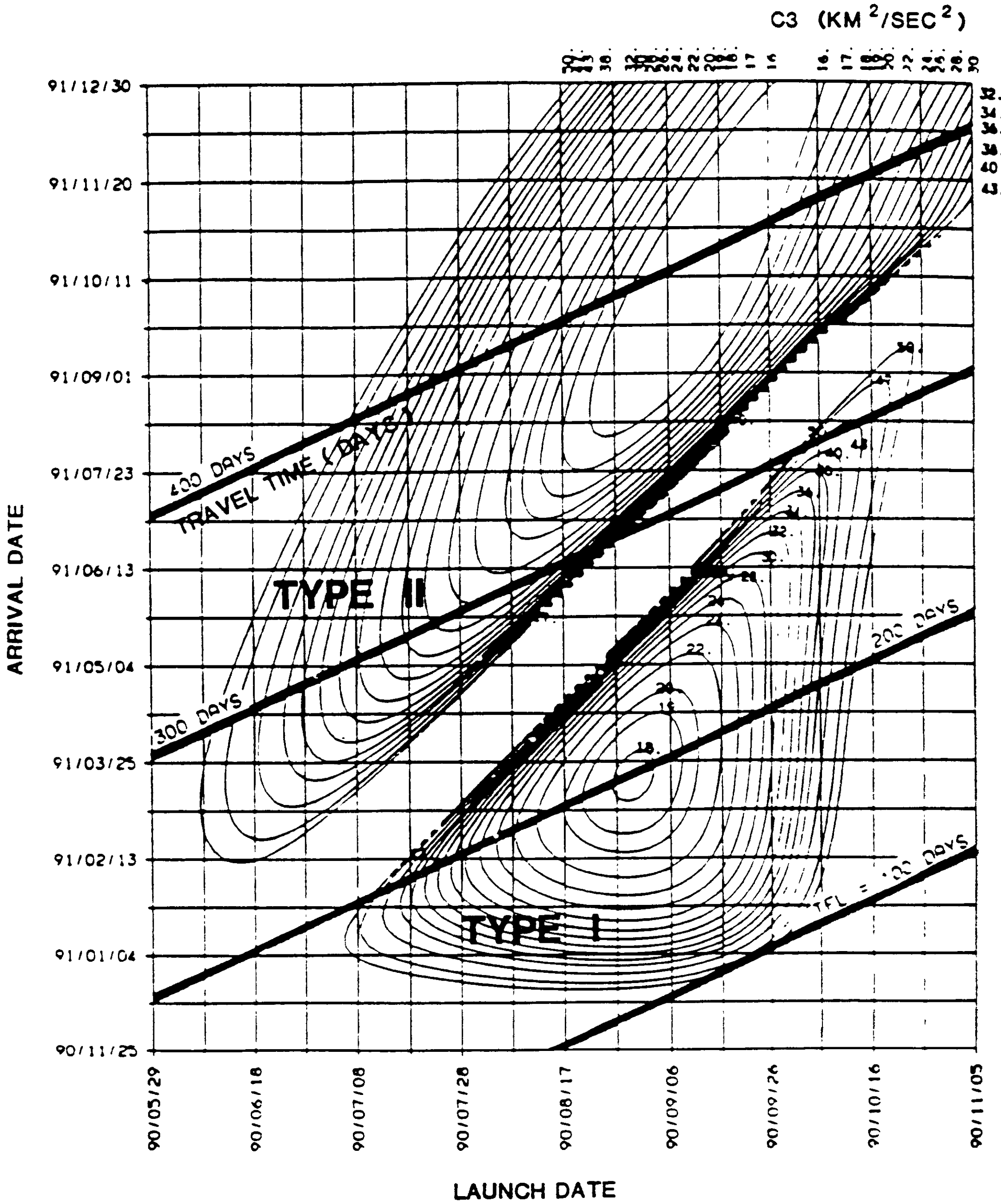

Figure V-2: Example "Porkchop" Curve for Earth-Mars Transfers

Once a spacecraft is pointed in the right direction at the right time to minimize the ΔV required for the trip, it then performs an orbital transfer maneuver. The same types of maneuvers can be used in going from LEO to the Moon or from the orbit of the Earth to the orbit of another planet orbiting the Sun. The basic orbital transfer maneuvers are minimum energy Hohmann transfers, high-energy transfers, and low thrust transfers.

In a Hohmann transfer, thrust is applied to move a spacecraft from its initial orbit into an elliptical orbit tangent to both the initial and desired final orbits. As the spacecraft reaches the desired orbit, thrust is applied again to circularize the orbit. For orbit transfers from lower- to higher-altitude orbits, these thrusts are applied in the direction the spacecraft is moving; in transfers from high- to low-altitude orbits the thrusts are applied in the direction opposite to the spacecraft's velocity. The ΔV required for a Hohmann transfer is

$$\Delta V = \sqrt{\frac{2GM}{R_1} - \frac{GM}{R_1+R_2}} - \sqrt{\frac{GM}{R_1}} + \sqrt{\frac{GM}{R_2}} - \sqrt{\frac{2GM}{R_2} - \frac{GM}{R_1+R_2}}$$

where R_1 is the radius of the initial orbit, R_2 is the radius of the final orbit, and M is the mass of the object (either the planet or the Sun) the spacecraft is orbiting. For a Hohmann transfer from a 500 km orbit to a geosynchronous orbit, the ΔV required is 3.8 km/s; for a near-Hohmann Earth-Mars transfer the necessary ΔV is 5.6 km/s.[161] (Remember that for an interplanetary transfer, the spacecraft must first reach escape velocity before conducting the transfer.)

While the Hohmann transfer is a minimum energy trajectory, it is also a local maximum for transfer time. The time spent travelling a Hohmann ellipse is

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161 Because of the eccentricity of the orbit of Mars, a slightly modified Hohmann transfer must be used for travel between the Earth and Mars.

$$t = \pi\sqrt{\frac{A^3}{GM}}$$

where A is the semi-major axis of the transfer ellipse, and M is the mass of the object the spacecraft is orbiting. The transfer time from a 500 km altitude orbit to geosynchronous orbit in a Hohmann transfer is 5 hours 15 minutes; the Hohmann transfer time from Earth to Mars is 260 days.

In a high energy transfer, more thrust is initially applied than in a Hohmann transfer, moving the spacecraft into an elliptical orbit that intersects and passes through the desired orbit. More thrust is applied when the intersection is reached, circularizing the orbit. The high-energy transfer is faster than a Hohmann transfer. Figure V-3 shows a Hohmann and a high-energy transfer.

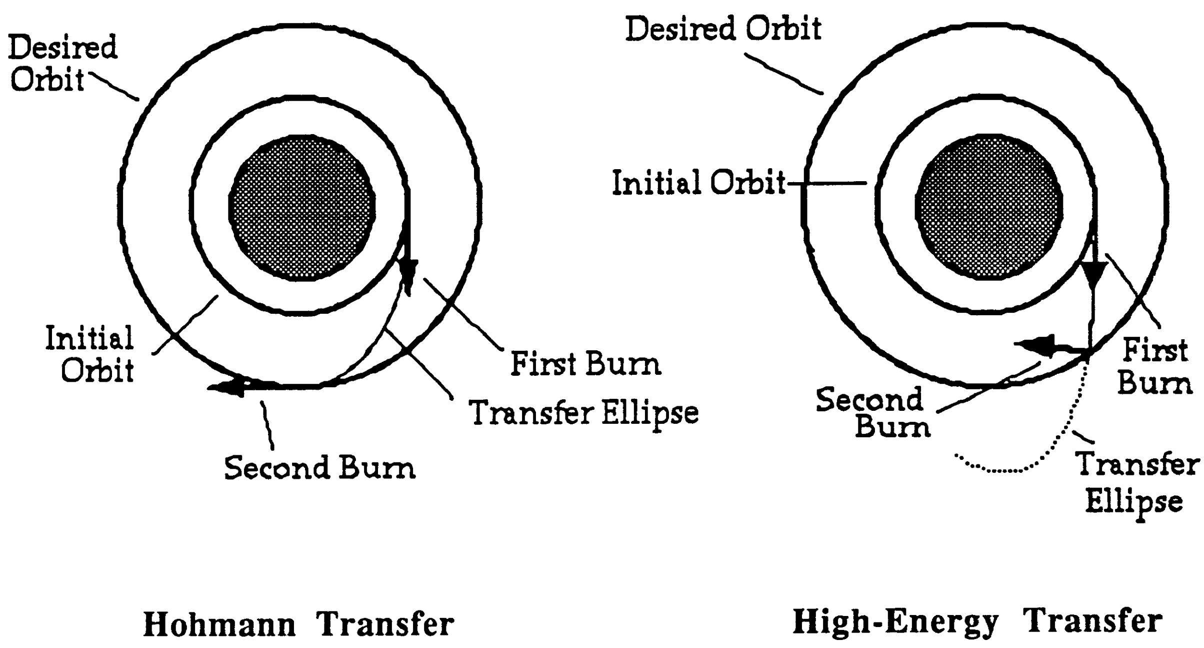

Figure V-3: Orbit Transfer Methods

If a spacecraft's propulsion system does not have enough thrust to carry out a Hohmann transfer (which requires large short-duration velocity changes), it can perform a low thrust transfer, where, as the orbit is elongated into an ellipse, thrust is repeatedly applied at the periapsis (the closest point to the planet) of the orbit, gradually enlarging it until it approximates the Hohmann ellipse, and then a series of burns are applied at apoapsis (the farthest point of the ellipse) as the desired orbit is reached. The energy needed for this kind of transfer is generally greater than that required for a Hohmann transfer. A fourth type of orbit transfer is used when a constant source of low thrust, such as a solar-powered ion thruster, is available. In this case the spacecraft accelerates in the direction of its motion, spiraling out until the desired orbit is reached. Figure V-4 illustrates a low impulsive thrust and a low constant thrust trajectory.

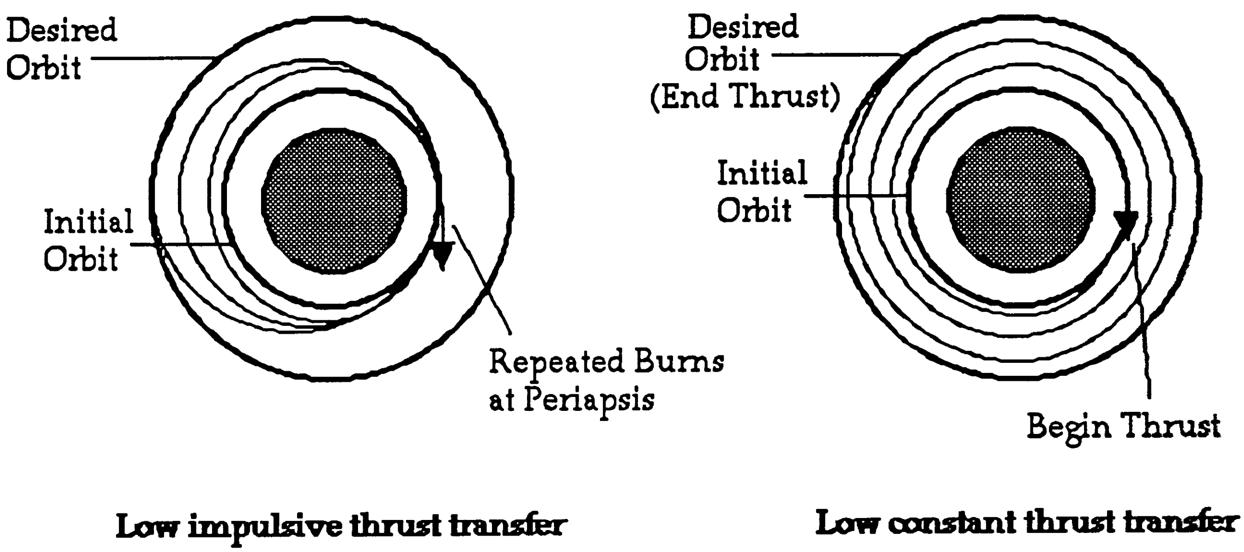

Figure V-4: Low Thrust Transfers

The time required to complete a low constant thrust transfer is[162]

$$t = \frac{\sqrt{\frac{GM}{R_1}} - \sqrt{\frac{GM}{R_2}}}{Acc}$$

[162]William E. Wiesel, Spaceflight Dynamics, New York: McGraw-Hill, 1989, p. 90.

where Acc is the acceleration of the spacecraft, R_1 is the radius of the initial orbit, and R_2 is the radius of the final orbit. The ΔV required for the transfer is

$$\Delta V = (Acc)(t)$$

or the difference in the velocities of the two orbits (higher than the ΔV required for a Hohmann transfer).

One possible maneuver that can be used to gain ΔV during an interplanetary trip is a flyby. In a flyby, a spacecraft gains ΔV by travelling close to a large body and using the body's orbital velocity and gravitational attraction to change the spacecraft's overall velocity vector, including changes in inclination. Though flybys can be a way to pick up "free" ΔV, they depend on particular alignments of the planets and can sometimes require complex and lengthy trajectories.

Once a spacecraft has completed its transfer orbit and come close to its target, it must usually change velocity again, either to land or to enter into a particular orbit. This maneuver can be accomplished with the reverse of the orbital transfers discussed above, or by aerobraking. The ΔV required to go into a circular orbit around the target planet is

$$\Delta V = \sqrt{V_{init}^2 + \frac{2GM}{R_{orbit}}} - \sqrt{\frac{GM}{R_{orbit}}}$$

where V_{init} is the spacecraft's relative velocity to the target body. The radius of the circular orbit that requires minimum ΔV to enter is

$$R_{min\ orbit} = \frac{2GM}{V_{init}^2}$$

but the spacecraft can be put into an elliptical orbit around the target planet for an even lower cost in ΔV.[163] One problem with using elliptical orbits in this manner, though, is that both the orbit's plane and the spacecraft's

[163]William E. Wiesel, Spaceflight Dynamics, New York: McGraw-Hill, 1989, p. 302.

position in the orbit must be correctly aligned for minimum energy travel either to and from the planets surface or into interplanetary trajectories. Often, this alignment can not be reached within the time frames of the mission, necessitating changes in the spacecraft's orbit and thus reducing the savings in ΔV.

One method of getting the necessary ΔV to enter orbit around a target planet is through using an aerobraking maneuver. Aerobraking involves using the atmosphere of a planet to slow the spacecraft into an elliptical orbit or a descent trajectory. Two problems with aerobraking are the large amount of heat generated during the maneuver and the necessity of having accurate information about the atmosphere at the time the spacecraft reaches the planet. The latter problem can be particularly difficult for a planet like Mars, where the atmospheric density can change by twenty percent from season to season.

Apart from flybys, the only proven way to gain ΔV in space is by using a rocket. Rockets operate by propelling stored mass backwards at a high velocity, thus forcing the rocket to travel forward. The faster the mass is propelled out the back, the more velocity the rocket gains. The following equation calculates the minimum amount of propellant that must be ejected to gain a particular ΔV

$$\frac{M_i}{M_f} = e^{(\Delta V / c)}$$

where M_i is the initial mass of the spacecraft, M_f is the final mass of the spacecraft[164], and c is the rocket's exhaust velocity. For a ΔV of 5.6 km/s (an Earth-Mars Hohmann transfer) using a liquid hydrogen/liquid oxygen rocket with an exhaust velocity of 4470 m/s, the ratio of initial to final mass is 3.5.

[164]Both mass figures include the mass of the payload, the mass of the structure, the mass of fuel and the mass of the rocket engine itself.

This means that to send 5000 kg on a Hohmann transfer to Mars requires at least 12,500 kg of propellant. Chemical rockets are the most commonly used type of rocket, but nuclear thermal rockets, ion engines, arcjets, and magnetoplasmadynamic (MPD) thrusters all can provide higher exhaust velocities, albeit with drawbacks.

Chemical rockets burn various substances to achieve exhaust velocities in vacuum from about 2500 m/s up to about 4750 m/s, with high thrust. (A rocket's thrust is the mass flow rate through the rocket times the exhaust velocity.) Solid rockets generally have lower exhaust velocities and cannot be stopped or restarted, but are simpler and generally less expensive than liquid-fueled rockets. Liquid fuel rockets utilize either storable or cryogenic propellants. Rockets using storable propellants have lower exhaust velocities than ones using cryogenics, but are simpler, cost less, and can be easily kept in space for long periods of time. Some hybrid liquid/solid systems have shown desirable safety and performance characteristics, but they have not yet been used in space.

Nuclear thermal rockets heat their propellant to a very high temperature to achieve exhaust velocities of 10,000 m/s and higher with high levels of thrust. For an Earth - Mars Hohmann transfer for a nuclear-thermal rocket with a 10,000 m/s exhaust velocity, only 3750 kg of propellant would be needed to deliver a 5000 kg payload. The performance of such rockets can also enable high-thrust transfers for interplanetary travel, thus reducing the duration of the trip. The rocket must also propel the mass of the reactor, which reduces the benefits of nuclear thermal rockets for missions with low ΔV requirements or small payloads. Nuclear thermal rockets are also expected to be more costly than chemical rockets, and the risk of an accident which might cause contamination of the Earth may preclude the use of nuclear thermal rockets in or below LEO. Nuclear thermal rockets have been tested, but never flown in space.

Ion engines, arcjets, and MPD thrusters all use electric power sources to accelerate particles from the rocket at very high velocities. While this method can achieve exhaust velocities of up to 80,000 m/s, a very large power source is needed to produce such velocities. The gains from the high exhaust velocities are thus balanced by the need to carry the large power source along for the mission. The power required for an electric thruster is

$$P = (1/2\eta)\, F\, c$$

where P is the required power, η is the efficiency of the thruster, and F is the thrust of the vehicle. This means that for the high exhaust velocities, accelerations will generally be very low. For example, an ion engine with an efficiency of .85 and an exhaust velocity of 30,000 m/s would require 17.7 kw of power to produce a thrust of 1 Newton. Since a typical power source might have a mass of 20 kg/kw of power, the power source mass would be 354 kg, and acceleration would be about .002 m/s. Electric rockets have only been used in Earth orbit applications to date.

Table V-1 lists the typical exhaust velocities and thrust levels for various propulsion technologies.

Table V-1: Rocket Propulsion Technologies

Technology	Exhaust Velocity (m/s) in Vacuum	Thrust
Solid Fuel	2,300 - 2,900	Very High
Liquid Fuel	2,600 - 3,200	High
Liquid Hydrogen/Liquid Oxygen	4,300 - 4,600	High
Nuclear Thermal	8,000 - 10,000	High
Electric Propulsion	10,000-50,000	Low

Operational Concerns for SEI Missions

SEI missions in space and on the surface of the Moon or Mars will require electric power, communications to Earth, and (if humans are involved) supplies of food, air, and water. Human presence also raises concerns about the effects of the space radiation environment and long-term microgravity exposure. These operational concerns will strongly affect the hardware requirements for the SEI.

Power

All space missions, piloted or robotic, require some kind of power source for their various subsystems (communications, guidance, command and data handling, life support, scientific instruments, etc.). The major space power sources available are radioisotope thermal generators (RTGs), nuclear reactors, solar photovoltaic and dynamic systems, fuel cells, and batteries. Both RTGs and nuclear reactor systems use thermoelectric couples or a thermionic energy conversion system to directly convert thermal energy to electric energy. With RTGs, the source of thermal energy is the decay of radioactive isotopes; reactors use the heat created by fission. Solar dynamic power sources use concentrated solar energy to power a heat cycle, producing mechanical energy which is then converted to electricity, while photovoltaic arrays convert solar energy directly to electricity. Finally, batteries and fuel cells (both of which can be recharged) use chemical reactions to produce electricity; in fuel cells the reactants are replaced during operation. Some of the properties of these different power sources are shown in Figure V-5.[165]

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[165]Griffin, Michael D. and French, James R., Space Vehicle Design, Washington: American Institute of Aeronautics and Astronautics, 1991, p. 398.

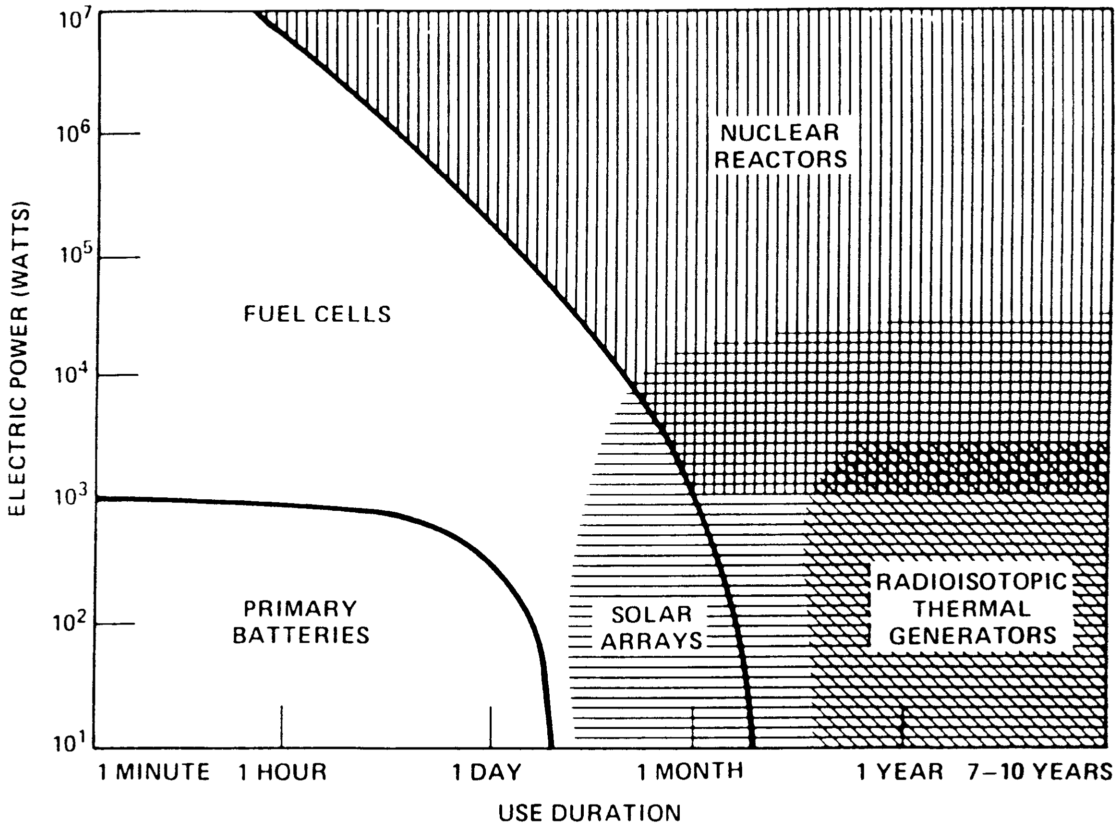

Figure V-5: Characteristics of Space Power Sources

Solar photovoltaic systems with battery storage are the most widely used space power system. The solar arrays power the spacecraft and recharge the batteries when the spacecraft is in sunlight, and the batteries power the spacecraft when it is in the dark. This works well in Earth orbit, when the periods of eclipse are short in duration, but on the Moon, for example, where darkness lasts for fourteen days, the size of the battery system required can become prohibitive. Solar power can also be used with fuel cells as storage;

this approach has not been tested in space, but seems to have a lot of potential.[166]

One problem with both photovoltaic and solar dynamic systems is that they generate less power the farther they are from the Sun. At the orbit of the Earth, the solar flux is about 1360 W/m^2, but the flux decreases as a function of the distance from the sun squared (thus the solar flux at the orbit of Mars is only about 590 W/m^2). The solar flux can be further reduced in areas with murky atmospheric conditions, such as on Mars during that planet's occasional lengthy dust storms.

Nuclear power sources have neither of the major problems of solar power sources, as they operate without the need for sunlight. On the other hand, there are some significant difficulties associated with the use of nuclear power in space. First, there is the risk of the spacecraft re-entering the Earth's atmosphere and dispersing radioactive debris. Even if extensive measures are taken to prevent such accidents, the perception of risk may result in a prohibition on nuclear power use in LEO.[167] RTGs have the additional potential problem of the low availability (and high cost) of Plutonium 238, the isotope generally used.

Communications

Communication between spacecraft and the Earth is another requirement for space travel. Communication is necessary for navigation, mission control, and data return. Communications in space are conducted in various frequencies of the electromagnetic spectrum. One of the major

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[166]Griffin, Michael D. and French, James R., Space Vehicle Design, Washington: American Institute of Aeronautics and Astronautics, 1991, p. 416.
[167]Aftergood, Steven, et. al., "Nuclear Power in Space", Scientific American, June 1991.

limitations is thus the speed of light (3×10^8 m/s). The one way trip time for a signal to travel between the Earth and the Moon is about 1.25 seconds; delays vary between 4.5 and 21 minutes for communications between the Earth and Mars, depending on the relative positions of the two planets.

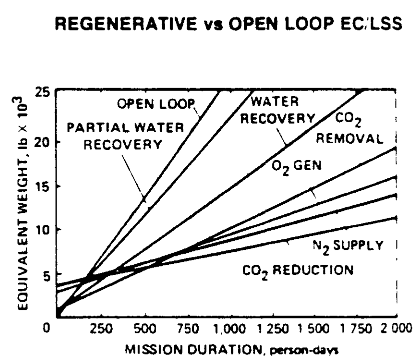
Another limitation is the strength of the signal needed to communicate over long ranges, which increases as a factor of the square of the distance. Communication over long ranges requires either strong signals or sensitive (and thus large) receiving antennae. Earth-Mars communication, though, is simple compared to feats that have previously been performed, such as communication with the Voyager spacecraft, which, when it encountered Neptune, was 11.6 times further away than the greatest distance between the Earth and Mars.

Communications on the electromagnetic spectrum also require a straight unblocked line between the transmitter and the receiver. If a spacecraft, surface base, or probe is on the far side of a planet, it will not be able to communicate with the Earth unless there are relay stations either on the planet or in orbit around it. This is particularly important for a base on the far side of the Moon, which, as it is never visible from the Earth, would be completely unable to communicate with the Earth without relays.

Concerns of Human Space Travel

One major concern in conducting space missions in which humans are involved is that the mass of supplies, including air, water, and food, needed to keep the astronauts alive can be very large. Humans consume about .63 kg of dry food per day plus 3.1 kg of water (including the water in food), plus about .81 kg of oxygen, for a total of about 4.5 kg of consumables per day.[168] For a 900-day Mars mission with a crew of four, 16,200 kg of consumables will thus be needed unless some of the consumables are recycled.

Both the United States and Russia have been working on such recycling efforts. Technologies have already been developed to recycle various components of a spacecraft's atmosphere. More sophisticated systems, including complete water recovery systems and schemes for growing plants for food and oxygen are at various stages of development. Figure V-6 provides a rough idea of how the use of regenerative systems can reduce overall mission mass as mission durations increase.



SEQUENTIAL STEPS IN LOOP CLOSURE

DEFINITION	DESCRIPTION
PARTIAL WATER RECOVERY	HUMIDITY CONDENSATE COLLECTION
WATER RECOVERY	POTABLE WATER RECOVERY AND TREATMENT FROM URINE AND WASH WATER
CO_2 REMOVAL (NONEXPENDABLE)	REPLACEMENT OF EXPENDABLE L OH WITH REGENERATIVE CO_2 COLLECTION TECHNIQUE
O_2 GENERATION	GENERATION OF O_2 THROUGH WATER ELECTROLYSIS USING RECLAIMED WATER
N_2 GENERATION	GENERATION OF N_2 THROUGH DISSOCIATION OF HYDRAZINE
CO_2 REDUCTION	DECREASE IN EXPENDABLE WATER BY RECOVERING PRODUCT FROM CO_2 REDUCTION (SABATIER) PROCESS

Figure V-6: Regenerative vs. Open Loop Life Support Systems[169]

Radiation effects are probably the most dangerous aspect of long-duration space flights. Radiation doses for humans are measured in Rem (roetgen-equivalent-man). The maximum allowable radiation dose for radiation workers is 5 Rem/year with a 250 Rem allowable career exposure; the general public can be exposed to .5 Rem/year. Current maximum

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[168]R.D. MacElroy and Harold P. Klein, "The Evolution of CELSS for Lunar Bases", Lunar Bases and Space Activities of the 21st Century, Houston: Lunar and Planetary Institute, 1985, p.624.
[169]P.D. Quattrone, "Extended Mission Life Support Systems", in The Case for Mars, San Diego: Univelt Inc., 1984, p.132.

allowable exposure for astronauts is 50 Rem/year, with a 300 Rem career limit. Different types of radiation cause different reactions, but in general, exposures of up to 75 Rem have little effect. Doses above 75 Rem may result in sickness, and once exposure rises above 300 Rem, death can result within days. Larger doses lead to increasingly certain and rapid death. In addition to the short-term effects, radiation damage can result in long-term effects such as increased risk of cancer.

The three types of radiation that present dangers to astronauts are trapped particles, cosmic radiation, and solar flares. Trapped particles are high energy electrons and protons that are concentrated in the Van Allen belts by the Earth's magnetic field. Cosmic radiation is an isotropic flux of energetic nucleii from outside the solar system. Solar flares are sporadic events that send large numbers of high-energy protons, alpha particles and some heavier nucleii out from the Sun. The atmosphere of Mars offers some protection against cosmic rays and solar flares, but the Moon and other bodies without atmospheres or magnetic fields do not.

The only serious danger from trapped particles in the inner solar system occurs in the Earth's Van Allen belts. These belts are distorted tori, open at the Earth's poles, which contain high energy electrons and protons. The belts begin at about a thousand kilometers above the Earth; the charged protons extend out to about ten thousand kilometers and the electrons to about thirty thousand kilometers above the Earth. Radiation doses from the Van Allen belts depend strongly on the shielding in the spacecraft. Astronauts in the worst part of the Van Allen belts will take a lethal radiation dose in a single day unless they have more than 1 gm/cm^2 of shielding. Even with 10 gm/cm^2 of shielding the astronaut may receive daily doses of up to 300 Rem.[170]

Cosmic radiation is an isotropic flux of energetic nucleii from outside the solar system with an intensity that varies inversely with the solar cycle. Without shielding, an astronaut will receive a cosmic ray dose of about 20 to 40 REM per year, depending on the solar cycle --uncomfortably close to the 50 REM annual limit set for shuttle astronauts.[171] Shielding against the very high-energy cosmic radiation is impractical because of the prohibitive mass that would be required.

Solar flares are occasional short-duration events in which the Sun emits large numbers of high energy particles. Flares occur in 11-year cycles with anywhere from zero to a dozen or more significant flares occurring per year, depending upon where the Sun is in the solar cycle. Radiation dose from solar flares are upwards of 100 Rem/hour; most solar flares will easily kill unshielded astronauts. Protection against solar flares requires significant mass. With shielding of 1 gm/cm^2, radiation doses from solar flares generally range from 500 to 2000 Rem. Shielding of 25 gm/cm^2 can reduce the maximum dose to under 25 Rem, which is the present 30-day astronaut exposure limit.[172] Because solar flares are short-duration events, it is possible to shield only a small part of the spacecraft and have astronauts stay inside the shielded area during the flare.

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[170] American Institute of Aeronautics and Astronautics, Final Report to the Office of Aeronautics, Exploration and Technology NASA on Assessment of Technologies for the Space Exploration Initiative, AIAA, December 31, 1990, p.66.

[171] Synthesis Group on America's Space Exploration Initiative, America at the Threshold: America's Space Exploration Initiative, U.S. Government Printing Office, Washington, 1991., p. 23.

[172] American Institute of Aeronautics and Astronautics, Final Report to the Office of Aeronautics, Exploration and Technology NASA on Assessment of Technologies for the Space Exploration Initiative, AIAA, December 31, 1990, p.66.

Long-term exposure to zero-gravity can also have deleterious effects on astronauts. The longest period of time that U.S. astronauts have spent in space is 84 days (in the final Skylab mission), although numerous Soviet astronauts have spent more time than that in the space station Mir (the longest stay to date was 366 days). The major effects of long-term zero gravity are mass loss of bone and muscle, but there have also been some (as yet not well understood) changes to the red blood cell and immune systems. It is believed that countermeasures to zero gravity, including exercise and drug treatment, can probably be used to minimize these effects,[173] though more data is needed to confirm this belief. One major concern is whether astronauts will be able to function on Mars after a long period without gravity; another is whether any of the deleterious effects of zero gravity will be permanent after the astronaut's return to Earth.

A final problem with long-duration missions is that operations in space are still inherently dangerous. The chance of an accident, such as a fire or an air leak, both of which can be fatal in space, increases steadily with time, as do mission risks due to equipment wearing out, and replacement spares being depleted. The odds that astronauts may have medical problems (such as appendicitis) also grow higher as the mission duration increases, as does the chance that their performance may be affected due to the long period of confinement and exposure to the hazards of spaceflight. Exacerbating this problem, it is generally not practical to mount quick rescue missions to destinations beyond Earth orbit.

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[173]Synthesis Group on America's Space Exploration Initiative, America at the Threshold: America's Space Exploration Initiative, U.S. Government Printing Office, Washington, 1991., p. 24.

VI. The SEI's Hardware Requirements

The March 1992 space policy directive on SEI strategy[174] states that the SEI "includes both Lunar and Mars elements, manned and robotic missions and supporting technology" and that the objectives of the SEI "include a return to the Moon - this time to stay - and human expeditions to Mars." Numerous technical schemes implementing these objectives have been proposed over the last decade, but no specific exploration plans have yet been officially sanctioned as part of the SEI. Broad possible strategies for human space exploration have, however, been laid out in the reports of the National Commission on Space[175], the Ride Task Force[176], the NASA Office of Exploration[177], the 90-Day Study[178], and the Synthesis Group.[179] Although the strategies proposed in these reports differ markedly, the demands of missions beyond Earth orbit have produced a limited set of hardware requirements. This chapter examines the hardware requirements of the SEI, focusing on those that may be satisfied by Russian space hardware.

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[174]George Bush, Space Exploration Initiative Strategy, National Space Policy Directive 6, March 9, 1992.

[175]National Commission on Space, Pioneering the Space Frontier, New York: Bantam Books, 1986.

[176]Sally K. Ride, Leadership and America's Future in Space, Report to the NASA Administrator, August 1987.

[177]Office of Exploration, NASA, Beyond Earth's Boundaries, 1988 Annual Report to the Administrator, 1988.

[178]NASA, Report of the 90-Day Study on Human Exploration of the Moon and Mars, November 1989.

[179]Synthesis Group on America's Space Exploration Initiative, America at the Threshold: America's Space Exploration Initiative, U.S. Government Printing Office, Washington, 1991, p.42.

Lunar Missions

The return of humans to the Moon is one of the fundamental elements of the SEI. Human exploration of the Moon was proposed in all five of the 90-Day Study's reference approaches to the SEI, and in all four of the SEI plans (or "architectures") presented in the Synthesis Group report. The tasks that the astronauts will perform when they reach the Moon are not yet clear; possible activities include lunar exploration, reduced gravity life sciences and materials experimentation, lunar-based astronomy, preparation for the exploitation of lunar resources, and the testing of hardware and procedures for later missions to Mars.

Although the SEI could include a wide range of possible lunar activities, almost any plan for returning astronauts to the Moon will require the same basic hardware elements. First, robotic precursor missions will be needed to prepare for the return of humans to the Moon. Next, when short-duration lunar excursions by astronauts begin, hardware will be required to transport the astronauts to the Moon and back, keep them alive during the journey and their sojourn on the Moon, and support them in whatever activities they will be conducting. As mission length increases, perhaps leading to the establishment of a permanent lunar base, additional hardware may be needed to meet the astronauts' changing transport, power, and life-support needs.

Robotic Precursor Missions

It is likely that any return of humans to the Moon will be preceded by robotic precursor missions. The report of the Synthesis Group incorporated lunar robotic precursors into three of its four architectures; the fourth, which proposed using the Moon only as a test bed for later Mars exploration, relied on data from the Apollo program and other previous lunar missions. The National Commission on Space, the Ride Task Force, the NASA Office of Exploration, and the 90-Day Study all scheduled robotic precursor missions before the return of humans to the Moon. It is not clear exactly what types of lunar robotic precursors will be used in the SEI; likely candidates include a polar orbiter, a network of ground stations, and rovers.

The first step for almost any return to the Moon is the development of a comprehensive data base of information about the lunar surface. The existing U.S. lunar data base, which comes largely from a series of Lunar Orbiter spacecraft flown during 1966 and 1967, is low resolution, has incomplete coverage of the lunar surface, and features a fairly high level of uncertainty.[180] A new, high resolution data base, that takes advantage of the many developments in remote sensing instruments since the 1960s, could be used to help select possible landing sites for future human missions, plot astronaut or rover traverses across the lunar terrain, determine areas of scientific interest, and find locations of valuable lunar resources, such as water ice.

The simplest means of acquiring such data is through the use of a lunar polar orbiting satellite. A polar orbit is preferred because a high inclination orbit is necessary to gather data on the lunar poles (where, it is believed, water ice might be located), and because such an orbit will eventually pass over every part of the Moon. Instruments for such a satellite would perform high-resolution imaging to determine surface topography, visible and infrared spectrometry to characterize the surface composition,

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[180] Leonard David, "Robots Must Precede Humans to Moon, Mars", Space News, November 12-18, 1990.

gamma ray spectrometry to measure elemental composition, and microwave sounding to determine the subsurface structure.[181] The orbiter might also gather magnetism and gravity data and use radar to determine geological and soil structure data down to depths of 10 to 20 meters.

A lunar polar orbiting satellite should not present any major hardware difficulties. The lunar orbit environment is similar to the environment in Earth orbit, so the spacecraft should be able to use fairly standard solar arrays, thermal systems, guidance, control, and station-keeping equipment. Nor will communications pose a significant problem, since the 2.5 second round-trip delay is unimportant to a satellite in orbit, and the loss of signal strength due to the distance from the Earth is not a problem for the large antennas available on Earth for deep space missions. Satellite lifetime need not be particularly long unless the orbiter is also functioning as a relay satellite for stations on the surface of the Moon. Finally, the instruments needed (with the possible exception of a radar sounding instrument)[182] are not particularly challenging to develop.

In addition to a global remote sensing data base, it might be deemed useful to develop a long-term data base of the geophysical and environmental conditions on the lunar surface. Such information, in addition to its intrinsic scientific value, could also be used to select sites for further scientific study, future landings, resource exploitation, or for bases for human occupation. This data base could be acquired by landing a network of small

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[181]American Institute of Aeronautics and Astronautics, Final Report to the Office of Aeronautics, Exploration and Technology NASA on Assessment of Technologies for the Space Exploration Initiative, AIAA, December 31, 1990, p.32.

[182]American Institute of Aeronautics and Astronautics, Final Report to the Office of Aeronautics, Exploration and Technology NASA on Assessment of Technologies for the Space Exploration Initiative, AIAA, December 31, 1990, p.32.

geophysical/environmental stations on the lunar surface. These stations, which might be either soft-landed or hard-landed, so as to penetrate into the lunar surface, would use a variety of instruments to collect their data. The Synthesis Group suggests stations which gather geophysical data with a magnetometer, an alpha particle counter, an x-ray fluorescence spectrometer, and imaging instruments, and which gather environmental data with instruments to measure meteorite flux, dust from secondary meteor impact, plasmas, fields, particles, and the lunar "atmospheric" composition.[183]

Finally, some scenarios for lunar exploration might benefit from detailed ground-level surveys of possible landing sites, and the terrain around them. This would improve the level of confidence about the landing site and would provide early astronaut crews with data that could direct their exploration efforts to the most interesting areas near the landing site. This task could be carried out by one or more lunar rovers carrying many of the same instruments as the geophysical/environmental station, perhaps with the addition of ground-penetrating radar to image the subsurface of a potential lunar base site.

The hardware requirements for a robotic lunar rover are fairly significant. First, it must survive a soft-landing on the Moon. Once the rover is on the surface, it will require some source of power (either RTG's or fuel cells) to keep it operating through the lunar night; alternately it could shut down for the night, but this could cause thermal problems. In addition, the rover will need to have either a high degree of autonomous control or to be in continual communication with the Earth as it moves. The 2.5 second

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[183]Synthesis Group on America's Space Exploration Initiative, America at the Threshold: America's Space Exploration Initiative, U.S. Government Printing Office, Washington, 1991, p.42.

communications delay from Earth certainly does not prevent teleoperation, though it would restrict the speed with which a rover could move; this could be troublesome if the rover needed to react rapidly (if it began to slide down a slope, for example). Control of a rover on the far side of the Moon would require the deployment of high altitude relay satellites. It is unlikely that such a vehicle would be needed, though, as most SEI plans focus on the lunar near side.

An alternative to using one large rover would be to use numerous small rovers. Such "mini-rovers" could not have the all the abilities of a large rover--for example, they could not carry large instruments--but they would have some significant advantages. First, the more numerous small rovers could cover a greater area than the single large rover. Second, the rovers could be designed with a slightly lower reliability than a large rover, because the loss of one small rover would not result in the failure of the mission. For the same reason, small rovers could be sent into treacherous terrain (such as steeply sloping areas) which the large rover could not risk entering. The debate over the relative worth of mini-rovers as opposed to larger rovers is far from over; the SEI might use either type (or both) on the Moon.

The hardware required to deliver the lunar robotic precursors to the Moon is a function of the mass of each robotic precursor, the ΔV required to land them on the Moon, and the time frame in which they will be launched. It is important to understand that the choice of a launch vehicle will probably be made during the hardware design process --the hardware will be designed so that it can be launched by a particular vehicle.

Because the robotic precursors will be designed to be launched by whatever vehicles are available, it is hard to estimate their mass. Historically, most similar robotic missions have had masses of 1000 kg or less: the Surveyor lunar landers weighed about 300 kg, the Viking landers about 1000 kg, the Voyager spacecraft around 800 kg, and the Soviet Lunokhod Moon rovers around 850 kg. There are no historical parallels to the network of ground stations, but the NASA 90 Day study estimated the mass of a geophysical station to be 100 kg (and the mass of a dual use manned/unmanned rover to be 1470 kg).[184] The mass of the rocket and fuel necessary to land on the Moon must also be added for any hardware that is going to operate on the lunar surface.

Two other parameters that will factor into the requirement for a launch vehicle are the required ΔV and the time frame of the missions. The minimum ΔV budget (calculated from the formulas in Chapter III) to travel from LEO to a low lunar orbit is about 3.9 km/s, and the ΔV to go from there to the surface of the Moon is about 2 km/s. Finally, although these robotic precursors are presumably to be the first SEI missions, they are unlikely to be needed until the late 1990s. (In the various architectures of the Synthesis Group, the lunar robotic missions are scheduled for launch in the 1999 - 2002 period.) Therefore, the requirements for the launch vehicles for SEI lunar robotic precursors are that they be available in the 1992 - 2002 period and that they be able to deliver payloads ranging from perhaps 500 kg up to about 3000 kg (for a large rover) into lunar orbit.

[184] National Aeronautics and Space Administration, "Lunar Transportation System", Viewgraphs from the 90-Day Study, 1989.

Initial Human Exploration on the Moon

Initial human lunar operations will require more and larger hardware than the robotic precursor missions. Regardless of the general focus of the lunar portion of the SEI, the first missions involving astronauts will probably be two to four week excursions. All four of the Synthesis Group architectures incorporate 14-day missions as the initial step in returning humans to Mars.[185] The Ride report also suggested beginning with one to two week missions, and the NASA 90-Day study proposed initial missions with duration of up to 30-days. Missions of this length will allow the astronauts to perform a significant amount of activities on the lunar surface but will not require the larger hardware infrastructure needed to support longer duration lunar stays.

Depending on the results of the robotic precursors and the general goals and pace of the SEI's lunar program, these early missions might have such varied tasks as preparing the site for a future base, performing scientific experiments, laying the groundwork for lunar resource utilization, or practicing for Mars exploration. The nature of the tasks the astronauts will be performing, however, will not have much effect on the mission's major hardware requirements because these requirements will be associated with the tasks of transporting the astronauts to the Moon and back and keeping them alive on the lunar surface. Hardware requirements for these missions can be divided into the broad areas of 1) lunar habitation, 2) lunar activities equipment, and 3) transportation to the Moon. The requirements for these

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[185]Synthesis Group on America's Space Exploration Initiative, America at the Threshold: America's Space Exploration Initiative, U.S. Government Printing Office, Washington, 1991.

three areas are closely linked; for example, larger habitats will require larger launch vehicles, and larger launch vehicles will enable larger habitats.

The astronauts on these exploratory lunar missions will need a pressurized habitat to live in, and base expeditions from, during their stays on the Moon. The habitat could be delivered to the lunar surface along with the astronauts (as in the Apollo program), or it could be sent to the Moon first in a separate cargo flight. To support the astronauts, any habitat will have a life-support system, an airlock, communications gear, internal walls and floors, a power supply, and kitchen and hygiene equipment. The major issues that must to considered in choosing a habitat design include transportability, required extravehicular assembly, mass, radiation protection, power, and volume. Each of these factors introduces constraints on the habitat design, as shown in Table VI-1.

Table VI-1: Major Issues and Constraints for Initial Lunar Habitats

Issue	Constraint
Transportability	•Each section must fit inside payload fairing of launcher •Must be able to survive lunar landing
Extravehicular activity	•Minimal EVA (in orbit or on Moon) to assemble
Mass	•Must be able to economically deliver habitat from Earth to lunar surface
Radiation protection	•Must protect astronauts against solar flares
Power	•Must supply reliable power for duration of mission
Volume	•Need sufficient habitable volume to meet astronaut's needs

There are numerous other issues that must be considered in the design of a lunar habitat, including thermal control, communications, and power distribution, but they do not drive the overall design to the same degree as the issues listed in Table VI-1.

The constraints listed in Table VI-1 can be used to narrow the range of designs for a lunar habitat. For example, the constraint on transportability means that assembly of a multi-module lunar habitat in Earth orbit is impractical because such a structure would probably not survive the lunar landing. Extensive assembly on the Moon can also be ruled out for these initial habitats, both because the astronauts will not have the time for such construction, and because they will need to live in the habitats soon after landing. The mass constraint may rule out habitat designs that offer complete protection against radiation.

The issue of the amount of radiation shielding required for these initial lunar habitats needs further examination. It will not be necessary to shield against cosmic rays because the unshielded radiation dose from this source will be, at most, about 5 rem in a month-long mission, well below the maximum allowable dose. On the other hand, it seems likely that the astronauts will need some shielding against solar flares. During the lunar night, the astronauts will be protected from solar flares by the mass of the Moon, but during the lunar day they will be directly exposed. Analyses predict that 25 g/cm^2 of shielding will be needed to reduce the radiation dose from the most severe flares yet observed to about 25 rem.[186] This mass can be very high--covering half of a Salyut-sized habitat in 25 g/cm^2 of shielding results in a total shielding mass of 12,000 kg. Since solar flares are fairly short-duration events, it may be necessary to shield only a small area of the habitat--a "storm cellar"--where the astronauts would stay for the duration of the flare. The lunar soil is a possible source of shielding material--while its use

[186] American Institute of Aeronautics and Astronautics, Final Report to the Office of Aeronautics, Exploration and Technology NASA on Assessment of Technologies for the Space Exploration Initiative, AIAA, December 31, 1990, p.66.

requires significant construction work on the Moon, it may be worth it to reduce the habitat mass.

It is not clear how large these initial habitats should be, since, like the robotic missions, their size will depend largely on the capability of various launch vehicles to deliver them to the Moon. The 90-Day study suggests using modified space station modules with a length of 8.2 meters, a diameter of 4.45 meters, and a mass of 12,000 kg. The size of these modules was driven more by the space station requirements,[187] however, than by conditions on the Moon or by projected mission needs. Historically, astronauts have been able to live in very cramped conditions for short durations--in the Gemini 7 flight, two U.S. astronauts orbited the Earth for two weeks with essentially no space to move around--but astronauts will need some space to perform various tasks inside the habitat. As a preliminary estimate, the mass of the habitat could range from about 6,000 kg to 20,000 kg, though this could increase if radiation shielding is incorporated into the habitat structure.

The lunar habitat will need electric power for life support, communications, on-board computers, and experiments. The choice of a power source will depend on both the amount of power required and on the duration of the stay on the lunar surface. The Synthesis group estimated initial lunar habitat power needs to be up to 50 kw, and the 90-Day Study suggested that initial power needs would be in the "tens of kilowatts." For a 14-day mission during the lunar day, a photovoltaic system would clearly be superior; for missions that extend into the lunar night, some kind of stored power would be required. Because of the importance of power to the habitat, it is crucial that the power supply be highly reliable.

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[187]which, in turn, were driven by the size of the Space Shuttle payload bay.

In addition to the habitat, the astronauts will require various other items of hardware to support activities on the lunar surface. They will need space suits to go outside the habitat; to travel to areas away from the habitat, they will require a lunar rover. For trips of more than a few hours it may be necessary to have a pressurized rover. Additional robotic rovers teleoperated from the lunar surface or from Earth may also be used; teleoperation of these rovers from the Moon would allow for much higher rover speeds because there would be no signal delay. Finally, the astronauts will also need special equipment to perform their various exploration and scientific tasks; such equipment might include scientific instruments, excavation equipment, or pilot plants for the use of lunar materials.

The single largest hardware requirement for initial human lunar exploration will be for the transportation of the astronauts and their equipment from the Earth to the Moon and back. This task is much more difficult than the transportation of the precursor missions, both because the masses involved will be much larger, and because the astronauts must be returned to the Earth. The presence of humans also necessitates greater margins of safety in both the vehicle design and in operational planning.[188] Because of these concerns, it may be preferable to launch large hardware items needed for human lunar presence, such as the lunar habitat, on separate cargo missions.

There are many possible methods of transporting astronauts from the Earth to the Moon and back. In the simplest method, a single launch vehicle delivers the entire payload, including the return vehicle, to the lunar surface.

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[188] An example of the safety requirement's impact on operational planning is that piloted missions will have to be designed so that the astronauts can abort the mission and return to the Earth in an emergency.

After the completion of the mission, the return vehicle leaves the lunar surface and travels back to the Earth. This approach has the advantage of simplicity, in that it does not require any rendezvous, but it does require an extremely large launch vehicle. As a very rough estimate, the booster required to launch even a minimal human lunar mission using this method would have to be at least double the size of the Saturn V.

The method of transportation used in the Apollo missions involved a lunar orbit rendezvous. This method begins with the launch of the entire mission on a single large launch vehicle, but upon reaching lunar orbit, the spacecraft separates into an orbiter and a lander. The lander then travels down to the Moon, leaving the orbiter in space. After the mission on the Moon is complete, the lander leaves the surface and rendezvous with the orbiter, which then returns to Earth. This approach does not require such a large initial launch vehicle because it involves the delivery of less mass down to the surface of the Moon and then back up again against the Moon's gravitational pull. One disadvantage of the lunar orbit rendezvous method, however, is that, due to the precession of the orbiter's path over the Moon, aborts from the lunar surface may require costly plane shifts to rendezvous with the orbiter. Depending on the safety rules for the mission, this could result in the lander being required to have large fuel reserves, which, in turn, would increase the overall initial mass and the size of the launch vehicle required.

A third possible method of travelling between the Earth and the Moon involves conducting an Earth-orbit rendezvous on the way to the Moon. In this method, segments of the mission are launched separately and rendezvous in LEO before travelling on to the Moon. One possible method of Earth-orbit rendezvous would be to launch the astronauts separately from the rest of the spacecraft, thus allowing the use of a less reliable launch vehicle to orbit the rest of the payload. Another method might be to launch the fuel separately from the spacecraft and then fuel the spacecraft in LEO. Yet another might be to launch the lunar landing modules and habitats separately from specialized transfer vehicles, which would rendezvous with the lunar modules and shuttle them back and forth between the Earth and the Moon. Such transfer vehicles could be refueled in Earth orbit and used repeatedly.

There are also alternate methods of returning to Earth from LEO. Rather than having the lunar mission carry a re-entry capsule all the way to the Moon, such a capsule could be left in LEO for the astronauts to rendezvous with on their return from LEO. Possible variations of this final Earth-orbit rendezvous include rendezvousing with a space shuttle, or rendezvousing with a space station and then transferring to a re-entry vehicle, such as the shuttle or a Soyuz capsule. One disadvantage to this method is that it constrains the return from lunar orbit until the orbital plane of the spacecraft being rendezvoused with is aligned correctly--additional fuel would be necessary to perform any plane changes necessitated by incorrect alignment of the planes.

The advantage of any of the methods involving rendezvous is that they reduce the total mass that must be initially be launched to orbit. However, there are three major disadvantages to using rendezvous. The first is that any rendezvous adds complexity to the mission and increases the probability of failure. The second is that any rendezvous will require either advanced automated rendezvous and docking equipment or the presence of astronauts, or both. The third reason is that it is more difficult to safely abort missions involving rendezvous, both because of the added complexity and because of the possible requirement for multiple out-of-plane transfers. These advantages and disadvantages must be weighed against each other in deciding which method should be used. It is not yet at all clear which method will be used in the SEI.

Nevertheless, a few basic hardware requirements can be derived from the transportation needs of the SEI. First, unless there are going to be a large number of rendezvous in LEO to start the mission, a heavy-lift vehicle will be required. The reason for this is that sending astronauts to the Moon, along with the transportation capability for them to return to Earth, requires that a very large initial mass be delivered to LEO. Even with multiple rendezvous, large launch vehicles are still needed--the AIAA's plan for early lunar exploration incorporated three rendezvous, but still required a launch vehicle that could deliver 75,000 kg to LEO.[189]

The Synthesis Group stated that "a heavy lift vehicle is the basic capability needed to support any lunar and Martian architecture", and recommended the development of one with a payload of from 150 metric tons up to 250 metric tons into LEO.[190] The AIAA assessment of technologies for the SEI also stated that the most critical near term need was "a heavy lift vehicle based on a modular design which can accommodate low Earth orbit (LEO) payloads initially in the 70-ton range and can then grow to meet Mars-mission lift requirements."[191] Even the NASA 90-Day study, which relied

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[189] American Institute of Aeronautics and Astronautics, Final Report to the Office of Aeronautics, Exploration and Technology NASA on Assessment of Technologies for the Space Exploration Initiative, AIAA, December 31, 1990, p.43b.
[190] Synthesis Group on America's Space Exploration Initiative, America at the Threshold: America's Space Exploration Initiative, U.S. Government Printing Office, Washington, 1991, p.31.
[191] American Institute of Aeronautics and Astronautics, Final Report to the Office of Aeronautics, Exploration and Technology NASA on Assessment of Technologies for the Space Exploration Initiative, AIAA, December 31, 1990, p.8.

heavily on assembly at the U.S. space station, stated that lunar missions "will require an Earth-to-orbit lift capability of approximately 60 metric tons."[192]

There may also be a need for smaller launch vehicles to support the lunar phase of the SEI. One requirement may be for a launch vehicle able to deliver astronauts to LEO to rendezvous with the rest of the Lunar mission hardware (previously delivered by a heavy-lift vehicle). Other possible, but less likely, needs might be to launch fuel to lunar transfer vehicles or to launch re-entry capsules into orbit to meet returning lunar astronauts.

The astronauts will also require a habitat for the journeys to and from the Moon. Depending on the mode of Earth-Moon travel selected for the early SEI, this habitat might also double as a lunar landing module or as an Earth re-entry vehicle. As the duration of even a Hohmann transfer to the Moon is only about five days, shielding this habitat against cosmic rays will not be necessary. Nor will shielding against solar flares probably be required, since solar forecasting predict the chances of a major flare during the brief transit time. The short transfer will also mean that this habitat's life-support systems will be mostly non-regenerable. Finally, the low power requirements and short duration travel mean that power could come either from on-board solar arrays or fuel cells.

The final major transportation hardware requirements will be for the transport of payloads between LEO and lunar orbit and between lunar orbit and the surface of the Moon. For both of these missions, high efficiency rocket engines will be needed. However, high efficiency, low thrust rockets, would be inappropriate for transfer to and from the lunar surface, because

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[192]NASA, Report of the 90-Day Study on Human Exploration of the Moon and Mars, November 1989, p. 5-2.

they could not provide enough thrust to keep from crashing; their use in transferring astronauts from LEO to lunar orbit would be ruled out by the length of time the astronauts would be forced to spend in the Van Allen belts. Therefore, standard chemical propulsion will be utilized, except possibly for the mission of transferring cargo from LEO to lunar orbit. (Nuclear thermal propulsion for these missions can be ruled out because of its high cost relative to conventional systems.)

Further Human Presence on the Moon

Following the initial exploratory expeditions to the Moon, it may be worthwhile to to pursue additional long-duration missions on the lunar surface, perhaps leading to the establishment of a permanent lunar base. The NASA 90-Day Study, the Ride Report, and all of the Synthesis Group Architectures featured long-duration lunar activities. Rationales for longer duration stays on the lunar surface could include expanded lunar exploration and scientific research (including astronomy), preparation for the exploration of Mars, and the exploitation of lunar resources. Long duration human expeditions to the Moon will have some of the same hardware requirements as the initial lunar missions, but the increased mission lengths will force changes to other requirements, and will create some entirely new ones.

The design of long-duration lunar habitats will be subject to different constraints from the design for the initial short-duration habitats. First, there will probably be more astronauts in the long-duration habitats, and each astronaut will require more space. Second, the growing lunar infrastructure will enable some habitat assembly on the Moon. Third, cosmic ray radiation will start to become a significant problem. Fourth, the habitat's power requirements will be larger, and the power source will have to operate through repeated lunar day/night cycles. Finally, the larger number of astronauts and the long duration of the missions will force either frequent resupply or the use of recycling in the environmental control and life-support systems.

The Synthesis Group recommended that long duration habitats have 30 to 100 cubic meters of volume per astronaut for long-duration stays. (This concurs with the Russian experience, in which pairs of astronauts have been able to endure for durations of up to a year in a space station with a volume of approximately 100 m^3.) As the crew of the lunar habitat grows, the total volume enclosed will also have to grow. Enlarging the lunar habitat could be accomplished either by connecting multiple small modules together, or by constructing one large, perhaps inflatable, structure. Either of these construction tasks will probably require the use of dedicated construction hardware.

In addition to a heavily shielded "storm cellar" to protect the astronauts during solar flares, the long-duration habitats may also need protection against cosmic rays. The annual cosmic ray radiation dose on the Moon is about 10 to 20 rem, with an uncertainty factor of about two.[193] While this is below the 50 rem NASA annual limit for radiation, routine exposure to such levels of radiation may be deemed excessive. Halving the radiation dose would require about 20 - 50 grams/cm^2 of shielding, which could either be part of the habitat, or lunar soil deposited on the habitat.

Long duration lunar missions will need reliable long-term power at levels probably higher than were required by the initial habitat. The increased

[193] American Institute of Aeronautics and Astronautics, Final Report to the Office of Aeronautics, Exploration and Technology NASA on Assessment of Technologies for the Space Exploration Initiative, AIAA, December 31, 1990, p.8.

power would be needed to satisfy the growing life support and operational needs of the habitat, as well as to support whatever activities were being pursued by the astronauts. The Synthesis Group estimated that power requirements for this stage of lunar habitation would begin at 100 kw and eventually to rise to 1 MW for a full lunar base. The NASA 90-Day study also suggested 100 kw as a starting point, with a final power level of 550 kw. The best power source to meet these requirements is likely to be a nuclear reactor. Development of nuclear electric surface power was recommended by the Synthesis Group as essential for the SEI.

Finally, the long duration stays and larger crews will require either that large amounts of consumables be delivered to the Moon or that consumables be recycled. For example, a crew of six at a lunar base will consume about 10,000 kg of oxygen, food, and water each year if there is no recycling. It is likely that any long-term lunar habitat will recycle some consumables and not others. If water was completely recycled, for example, the amount of consumables needed could be reduced by up to two thirds. Some recycling of consumables may also be conducted in an demonstration mode that will not initially results in overall mass savings.

In addition to the habitat, there would also be some new hardware required to support operations on the lunar surface. New hardware might be required to aid in the construction of the larger habitats, whether in moving modules around or in collecting lunar soil for use as radiation shielding. Other new hardware requirements would depend on what types of lunar activities were being pursued at the lunar base. Possible requirements could be for larger-scale units for mining or processing lunar resources, new telescopes and other astronomical facilities, improved long-range rovers, or even for small rocket-powered craft that would be used to travel to sites too distant or inaccessible to reach in a rover.

Transportation requirements for the extended human presence on the Moon would not be very different from what they were in the early stage of lunar exploration. While the new habitats might be larger, requiring a more powerful launch vehicle or multiple rendezvous in LEO, they could also be the same size as the earlier habitats. In fact, the largest changes in the transportation between the Earth and the Moon in this phase of the SEI would probably be due to the introduction of new launch and transfer vehicles in the early years of the 21st century. Two new transportation hardware requirements, however, could result from the extended human presence on the Moon. The first of these is a possible requirement for a vehicle to resupply the lunar habitats. Such a vehicle might be necessary if new crews coming to the lunar base could not bring sufficient consumables with them. The second is for a highly efficient transfer vehicle for travelling between the Earth and the Moon. Such a vehicle would become more cost-effective to develop as traffic between the Earth and the Moon increased.

Mars Missions

The second major SEI objective is the exploration of Mars by astronauts. Human exploration of Mars was included in all of the 90-Day Study's and the Synthesis Group's approaches to the SEI, and was also suggested by the NCOS and the Ride Report. The exploration of Mars is expected to be directed towards answering a number of scientific questions about the planet, and will involve study of its present and past geology, atmosphere, and climate. A possible additional task may be to determine the feasibility of using Martian resources.

The exploration of Mars is in many ways more challenging than the exploration of the Moon. The basic difference is not the energy required to get there--in energy terms a low Mars orbit can be easier to reach than the surface of the Moon. Rather, the main difference is that the vast distances between the Earth and Mars, and the changing alignments between the two planets, necessitate extremely long-duration missions. This does not greatly effect robotic missions, but it adds numerous difficulties to any missions involving human presence.

Martian Robotic Precursors

It is virtually certain that robotic precursor missions will be sent to Mars before any human exploration begins. Because existing data on Mars is sparse, and transporting humans there extraordinary difficult, it may be worthwhile to conduct an extensive Martian robotic precursor program. NASA's 90-Day study recommended sending a global network mission with two orbiters and multiple surface stations, a sample-return mission with a rover, a four-satellite site reconnaissance mission, and five additional rovers to study potential landing sites and prepare for human presence.[194] The Synthesis Group recommended launching two orbiters for site reconnaissance and communications, two rovers to certify and characterize possible landing sites, and (for one architecture) a network of eight ground stations to take geophysical and environmental measurements.[195]

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[194]NASA, Report of the 90-Day Study on Human Exploration of the Moon and Mars, November 1989, p.3-10 - 3-12.

[195]Synthesis Group on America's Space Exploration Initiative, America at the Threshold: America's Space Exploration Initiative, U.S. Government Printing Office, Washington, 1991, p.38.

One of the most important tasks that must be accomplished before human explorers arrive will be the selection of suitable landing sites. Landing sites will probably be located near areas of scientific interest, or near concentrations of significant resources; the identification of such sites will require a global database of Martian topography and surface composition. Data will also be needed to ensure that potential sites are suitable terrain for landing (unlike the boulder fields encountered by the Viking landers), for emplacing large habitats and power sources, and for sustaining surface travel. Detailed information on the surface topography and composition and some knowledge of the subsurface structure will be required to determine if each site is safe.[196]

The hardware needed to acquire the necessary site selection data will probably include one or more polar orbiting satellites and a number of surface rovers. It may be necessary to have separate satellites to acquire the global science/resource database and to investigate possible landing sites. This is not only because acquiring high-resolution landing site data may require a lower orbit than is optimal for a satellite collecting a global database, but also because the selection of candidate landing sites may have to await lengthy study of the data returned from the global imaging satellite. Rovers will be needed to survey potential landing sites in detail, acquiring data on the local topography, available resources, subsurface structure, and chemical composition (including analysis of the soil for possible toxicity.)[197]

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[196]Each site will have to be examined because of the wide variation of conditions over the Martian surface. For example, the peak of Olympus Mons is almost in vacuum, the polar regions are covered with ice, and some valleys may contain deep layers of ash or dust.

[197]The Viking landers found the Martian soil to be highly reactive, but did not have sufficient analytic capability to determine if it might be toxic.

In addition to preparing for human bases, robotic precursors may also be used to gather scientific data about Mars. The primary scientific goals for Mars exploration include gaining knowledge about climate change, searching for evidence of life, and learning about the geology and formation of Mars. Much of the hardware needed to acquire scientific data will be very similar to that used to prepare for human presence; individual hardware items will probably be used for both purposes. For example, rovers may be used to conduct preliminary science surveys of areas near potential landing sites, or to explore sites which are unsuitable for human exploration, and the same satellites that are looking for landing sites could also observe scientifically interesting areas.

One science mission that could require specially dedicated hardware would be the long-term study of the Martian surface environment and climate. In addition to satellite-based instruments, this task would require measurements from a number of different areas on the Martian surface and, possibly, at different altitudes in the Martian atmosphere. Surface observations could be made by a widely distributed network of small environmental/geophysical stations that could be soft or hard landed or emplaced by rovers. These stations would measure seismic events, wind speeds, atmospheric pressure, solar flux, and other local conditions. Long-term measurements from different altitudes in the atmosphere, if such information was deemed necessary, would require the use of sensors carried on a large balloon or unpiloted airplane.

The most technologically challenging precursor Mars mission would be to return samples of the Martian soil and atmosphere to Earth. The return of samples to Earth can produce a much greater harvest of scientific information than the analysis of the same materials on Mars, because far better and more varied testing facilities are available on the Earth. A thorough robotic Mars sample return mission would sample both surface and subsurface rocks at various sites, which would require the use of a rover.[198] Unlike other precursor missions, a sample return mission would also need a rocket to leave the surface of Mars and enter a trans-Earth orbit.

Finally, there are a number of other miscellaneous activities that may have to be performed by robotic precursor missions before human explorers arrive. One of these is the characterization of density structure of the upper Martian atmosphere as a function of latitude and longitude, time of day, and season. This information, which is needed if aerobraking is to be used at Mars, would require at least a satellite-based instrument, and could also require atmospheric probes.[199] Other precursor missions may be needed to establish surface navigation aids, and to test hardware and procedures for the human missions.

Martian precursor satellites would have slightly different hardware requirements than their lunar equivalents. All Martian robotic missions would have to be slightly more reliable than their lunar counterparts, both in order for them to survive the long journey to Mars, and because it would be more difficult to replace them if they failed. Martian satellites would also have slightly different communications, power, and thermal subsystems than their lunar equivalents. The greater distance to the Earth would necessitate more powerful communications equipment, and the reduced solar flux would necessitate larger solar panels and a different spacecraft thermal

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[198] Office of Technology Assessment, Exploring the Moon and Mars, Washington D.C.: U.S. Government Printing Office, July 1991, p.76.

[199] American Institute of Aeronautics and Astronautics, Final Report to the Office of Aeronautics, Exploration and Technology NASA on Assessment of Technologies for the Space Exploration Initiative, AIAA, December 31, 1990, p.49.

balance. Solar panels would still be preferable to nuclear power, though, for the small power needs that such satellites would probably require.

Martian rovers may be quite different from their lunar counterparts. First, the existence of a Martian atmosphere will mean that Mars rovers will have to be resistant to flying dust, rather than to vacuum welding. Second, the 24.6 hour Martian day and the low solar flux at the surface may mean that Mars rovers will need a different power source than their lunar equivalents. The optimal power source for Martian rovers isn't obvious, though; the low solar flux (especially during dust storms) will reduce the efficiency of a photovoltaic system, but it is not clear if a radioisotope thermal generator power source would be sufficiently superior to be worth the increased cost. Finally, the great distance between Mars and the Earth will mean that precursor Mars rovers will need a different communications and control system from lunar rovers. To avoid having to equip each rover with a large high power antenna, Mars rovers will probably communicate with Earth via a satellite in Mars orbit. This would optimally be a separate satellite in synchronous orbit over the rover (if the rover is at a low enough latitude), but it could also easily be another capability of a global reconnaissance or site selection satellite.

The time delay for communications between Earth and Mars, which can be over 40 minutes, without even considering the delay caused by any satellite relays, will render teleoperation from Earth almost impossible; any precursor Mars rover will require a high level of autonomous control. This would seem at first to rule out the use of mini-rovers on Mars, but rapidly shrinking computer and improved autonomous control capabilities may make highly autonomous mini-rovers feasible by the time they would be needed. Otherwise, the advantages and disadvantages of Martian mini-rovers would be fairly similar to those of lunar mini-rovers.

Except for the case of a robotic sample return mission, the transportation requirements for these precursor missions are not particularly formidable, as transportation will be required in only one direction.[200] Since there will be no particularly urgent time constraints on these robotic spacecraft, they will probably sent on minimum-energy trajectories. For the Earth-Mars transfer, such trajectories are available about every 26 months. The ΔV required for these minimum energy transfers varies for each launch window, but is generally about 4 km/s to begin the transfer to Mars. An additional ΔV of around 1.5 km/s is required to enter orbit around Mars from a minimum energy trajectory, and approximately 1.7 km/s beyond that needed to reach the Martian surface using parachutes and landing rockets.

These ΔV requirements can be lowered somewhat by utilizing swingbys of Venus and aerobraking at the orbit of Mars. Venus swingbys will increase the flight time to Mars, but this is not particularly important for robotic missions. Aerobraking at Mars is significantly more problematic. First, as discussed earlier, it will require a greater understanding of the Martian atmosphere. Second, it will require major technology advancement, and will incorporate a high level of risk.[201] If aerobraking technology is sufficiently developed, though, it could reduce or eliminate the need to "expend" ΔV to enter orbit around Mars.

200Requirements for two-way transportation between the Earth and Mars are discussed in the next sub-section.

201Synthesis Group on America's Space Exploration Initiative, America at the Threshold: America's Space Exploration Initiative, U.S. Government Printing Office, Washington, 1991, p. A-41.

Conventional chemical rocket engines should be sufficient to launch any Martian precursor mission. The masses of the Martian precursors should not be very different from their lunar counterparts --in the range of 500 to 3000 kg delivered to Mars orbit, and the ΔV's will also be in the same range as for lunar missions (perhaps lower for some trajectories involving swingbys of Venus). As with the lunar precursors, the Mars missions will probably be designed with existing launch vehicles in mind. In summary, the launch requirements for the Martian precursors will be that the launch vehicles must be available in the 1999 - 2005 time period and be capable of launching payloads of 500 to 3000 kg to the orbit of Mars.

Humans to Mars

The hardware required for any human mission to Mars will depend largely on the type of orbital transfer used between the Earth and Mars. The choice of the type of transfer will, in turn, be based upon the availability of various technologies and on tradeoffs made between reducing mission time and reducing the overall propulsion requirements. The basic problem is that while transfer opportunities between the Earth and Mars that do not require very high ΔV expenditures do exist, they result in very long overall trip times. The longer journeys expose the astronauts to more radiation, increase the deleterious effects of exposure to microgravity, and increase the amount of supplies needed. This problem can be dealt with either by using high-energy propulsion to reduce transfer times, by designing the mission hardware for very long-duration flights, or by a combination of the two.

Table VI-2 lists the types of transfers most likely to be used in SEI. All of the values in the table are approximate; the ΔV numbers do not include the ΔV required to enter orbit around the Earth or enter the Earth's atmosphere on the return leg of the trip.[202] A conjunction-type mission basically uses near-Hohmann transfers to travel from Earth to Mars and from Mars to the Earth. Opposition class missions involve a different alignment of the two planets and require either a deep-space propulsive maneuver or a Venus flyby on one leg of the mission. The fast versions of these two types of missions are achieved by expending extra ΔV to speed up the travel between the planets. Finally, the split-sprint method involves very high ΔV expenditures to achieve nearly direct Earth-Mars flights.

Table VI-2: Earth-Mars-Earth Transfers[203]

Transfer Type	Total ΔV (km/s)	Time in Space (days)	Time on Mars (days)
Conjunction	9	600	400
Fast Conjunction	19	300	580
Opposition	15	400	30
Fast Opposition	26	340	30
Split Sprint	29	210	30

Another concept that has been proposed for Earth-Mars transfers is the use of "cycling" spacecraft, which would travel between the orbit of Earth and the orbit of Mars, using gravity assists to repeatedly return to the vicinity of the planets. Astronauts would use high speed transfer vehicles to rendezvous with the cycling spacecraft as it neared the planet, perhaps as it passed through one of the Lagrange points. The advantage of this scheme is

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[202]The return to Earth may involve entering Earth orbit, "parking" at a Lagrange point, or making a ballistic re-entry into Earth's atmosphere.

[203]Derived from data in American Institute of Aeronautics and Astronautics, Final Report to the Office of Aeronautics, Exploration and Technology NASA on Assessment of Technologies for the Space Exploration Initiative, AIAA, December 31, 1990.

that it only requires that the Earth-Mars habitat be put into the transfer orbit once. The main disadvantage is that it requires a high mission rate to become cost-effective, so much so that it may not be appropriate before the mid-21st century.[204]

An advanced propulsion system will probably be required for missions using any but minimum-energy conjunction transfers. As the required ΔV's for the missions rise, it becomes ever more necessary to use a rocket with an extremely high exhaust velocity. For example, a storable propellant chemical propulsion system would need about five times as much propellant as a nuclear thermal rocket for a conjunction class mission, but it would need more than 200 times as much fuel as a nuclear thermal rocket for a split/sprint mission. The nuclear thermal rocket is probably the only advanced propulsion system with the requisite thrust and exhaust velocity to perform high-energy transfers that can be available in the time frame of the SEI. While electric rockets have higher exhaust velocities, they are not able to produce the necessary thrust to achieve rapid Earth-Mars transfers.

Electric propulsion, however, may be useful for cargo missions between the Earth and Mars. For these missions, lengthy travel times will not be a problem, as the cargo will not be affected by an extra few hundred days in space. The high exhaust velocities, however, will mean that fuel expenditures for the transfer will be low, reducing the initial mass that will have to be delivered to LEO. The power source needed for Mars cargo missions will have to be fairly large; the Synthesis Group and the AIAA estimated power requirements for an Earth-Mars electric rocket transfer

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[204]Synthesis Group on America's Space Exploration Initiative, America at the Threshold: America's Space Exploration Initiative, U.S. Government Printing Office, Washington, 1991, p. 63.

vehicle to be about 5 MW. Nuclear power is the optimal source to achieve these power levels.

The SEI may end up using different transfer schemes as the exploration of Mars progresses. Assuming the necessary propulsive hardware is available, the first mission might be a split sprint mission with a short stay on Mars. (For this and other trips with short stay times on Mars, it would be important to schedule the Mars landing for a time when global dust storms are not likely to be occurring.) This initial mission would gain experience in working on Mars and bring back samples (whether for scientific or resource exploitation purposes) that could be used to help plan the next mission, which might utilize a fast conjunction transfer with a long stay on Mars. If high energy propulsion hardware is not available, however, the initial human mission would probably use a conjunction type transfer, resulting in a 400 day stay on Mars.

The habitats needed to support human Mars exploration will vary depending on the type of transfer used. For example, the type of habitat needed for a 400-day stay on Mars will be very different from a habitat used for a 30-day stay, as it will have to be larger, more efficient in recycling consumables, and more reliable. No matter what transfer is utilized, it is very unlikely that a single habitat will be used for both the space and Mars segments of any mission. One reason is that it would require a prohibitive amount of fuel to transport a large radiation shielded habitat between Mars orbit and the planet's surface. Another reason is that the habitat requirements for the two environments differ, and trying to satisfy both sets of requirements would probably result in an expensive, heavy, and complex design. The SEI will probably incorporate separate round-trip space habitats and Mars surface habitats; the surface habitats will probably be sent to Mars in a dedicated cargo mission.

The requirements for habitats used during Earth-Mars transfers will be very different from those for habitats used in Earth-Moon voyages. First, because of the long mission duration, the Mars transfer habitats will need radiation shielding against both solar flares and cosmic rays. Second, the issue of long-term exposure to microgravity may also force some design modifications. Third, the astronauts will need a reasonable amount of living space and, probably, regenerable life support systems. Finally, a long-duration power source will be needed. In general, each of these requirements will grow more onerous as the transfer times rise.

The space habitats used for Mars missions will require significant amounts of shielding. First, the very high probability of a large solar flare during the time spent in interplanetary transfers will necessitate that the habitat have a heavily shielded "storm shelter." Second, the cosmic ray dose over the duration of all but the most high-energy trips is likely to exceed recommended safe limits. Although the astronauts can take shifts in the radiation storm shelter to lower overall cosmic ray dose, it seems probable that upwards of 25 grams/cm^2 of shielding will be used over much of the transfer habitat. This shielding could be partially made up of fuel and consumables in order to minimize the extra mass required.

Another problem caused by long transfer times is astronaut deconditioning due to long-duration microgravity exposure. In addition to possible long-term effects, such deconditioning might leave the astronauts unable to function when they reach Mars. Other than reducing the trip times, the primary methods of dealing with the problem would be to develop countermeasures (such as exercise) to the effects of long-term microgravity, or to provide artificial gravity in the transfer vehicle. Artificial gravity could be produced by rotating the transfer spacecraft, but the spacecraft would either have to be very large or spun very rapidly. Either of these strategies would cause problems: large rotating spacecraft would probably require multiple launches from Earth and significant assembly on orbit, while small, rapidly rotating habitats would have some unsettling effects on the astronauts inside them due to the gravity gradient and the coriolis forces that would be created.

The astronauts in these habitats will also need relatively roomy accommodations, and enough air, food, and water to last them for the duration of the round-trip interplanetary transfer. The problems here are the same as those discussed for the long-duration lunar habitat--each astronaut will require sufficient personal space and some level of recycling of consumables will have to be achieved. Again, as the transfer times increase, the amount of space needed by the astronauts will also increase, as will the total mass of air, food, and water required.

In all probability, the space habitat will also be the site of some scientific and exploration-related activity. During the deep space segment of the flight, astronauts may perform astronomical observations or conduct microgravity experiments. Once the mission nears Mars, teleoperation of Mars rovers may begin. In the event of dust storms that delay landing on Mars, such teleoperation activities may continue for an extended period of time. The hardware requirements for these on-board science activities will be small; they will include power, communications, and possibly a location on the outside of the habitat.

Finally, the space habitat will need a reliable source of power to meet the needs of its various subsystems, the astronauts, and any onboard experiments. The Synthesis Group estimated space habitat power requirements for a Mars mission to be up to 20 kw.[205] As the spacecraft will be in sunlight for the entire duration of the transfers, photovoltaic systems will probably be the optimal power source. Battery storage would probably be needed to augment the photovoltaic system for periods when the habitat is in orbit around Mars.

The design of Mars surface habitats will depend strongly on whether the stay on Mars will be for a month or for over a year. The differences between long-duration and short-duration habitats were already discussed in the lunar exploration section of this chapter; most of what was said there holds true for Mars. One difference between Martian and lunar habitats is that radiation shielding will probably not be needed for the Martian habitat, since the atmosphere of Mars provides significant shielding against both cosmic rays and solar flares.

The power requirements for Mars habitats would probably be similar to those of the equivalent lunar habitats. The optimum power source for the Martian habitats is not clear, however. If power requirements are below 50 kw, for example, photovoltaic arrays might be the optimal power source. While the solar flux at Mars is lower than it is on the Moon, the short day/night cycle would mean that photovoltaic/battery systems would still be fairly efficient. If the habitat power needs are large, a nuclear reactor will probably be the best power source for long-duration missions; high power requirements for short duration missions might be met by the use of photovoltaics and fuel cells.

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[205] Synthesis Group on America's Space Exploration Initiative, America at the Threshold: America's Space Exploration Initiative, U.S. Government Printing Office, Washington, 1991, p. 69.

Various other items of hardware will be used by the astronauts to carry out the exploration of Mars. For journeys outside the habitat, the astronauts will require a spacesuit designed for the gravity, thermal, and atmospheric conditions on Mars--existing spacesuits would be too heavy and bulky for long-term Mars exploration. Rovers, both pressurized and unpressurized, will be needed to carry astronauts to areas of scientific interest beyond the immediate vicinity of the habitat. Teleoperated rovers will also be needed to explore interesting areas of the planet that the astronauts will be unable to reach. Such teleoperation may require the presence of a communications satellite, perhaps one left over from the precursor missions.

The final major hardware requirements for the Mars portion of the SEI will be for the hardware required for travel between the planetary surfaces and the Earth-Mars transfer vehicles. Any piloted Mars mission will almost certainly involve both Earth orbit and Mars orbit rendezvous. Earth orbit rendezvous will be necessary to assemble and fuel the large transfer vehicle, and to deliver astronauts to it. Mars orbit rendezvous will be necessary because it would be prohibitively wasteful of fuel to deliver the large transfer habitat to the Martian surface and back. Finally, Earth-orbit rendezvous may again be required to return the astronauts to Earth at the end of the mission.

The SEI's Mars missions will require both a heavy-lift vehicle and significant assembly on Earth orbit. These will be required because of the vast size of a Mars mission. The AIAA estimated that a 4-6 crew transfer habitat would have a mass of from 40 to 55 tons.[206] Delivering such a transfer crew module to Mars and back on a low energy transfer with cryogenic rockets

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[206] American Institute of Aeronautics and Astronautics, Final Report to the Office of Aeronautics, Exploration and Technology NASA on Assessment of Technologies for the Space Exploration Initiative, AIAA, December 31, 1990, p. 47b.

would require at least 300 tons of fuel; to carry the same transfer vehicle to Mars on a split sprint using a nuclear thermal rocket would require at least 850 tons of fuel. Since a heavy lift vehicle capable of putting 350 to 900 tons in Earth orbit is not likely to be developed in the time frame of the SEI, significant on-orbit assembly and refueling operations will be necessary. Heavy-lift vehicles would help to reduce the amount of assembly, and would also allow large components, such as a Mars habitat, to be delivered to orbit in a single piece, thus simplifying their design. Smaller launch vehicles, as well as safer launch vehicles suitable for launching humans, may be used to ferry astronauts, fuel, and mission hardware up to the transfer vehicle.

On the return trip to Earth, the large transfer vehicle will probably be left in a high orbit for possible refurbishment and re-use; it could also be left at a Lagrange point to lower future ΔV requirements for it to leave the Earth's vicinity or to allow for refueling with lunar materials. The choice of the parking location for the transfer vehicle will depend on the hardware available to reach it there, the stability of the orbit, the potential for re-use, and any possible radiation hazard if nuclear power is involved.[207] The astronauts could either be met at this parking orbit by a re-entry vehicle (either expendable or reusable), or could use a transfer vehicle that they had brought with them to re-enter the Earth's atmosphere.

Finally, hardware will be needed for travelling between Mars orbit and the surface of Mars. A small crew excursion module, similar to that used in the lunar missions, will probably be used to deliver astronauts between these locations. Since the mass of such a module is likely to be small (the AIAA

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[207]The Synthesis Group suggested ejecting reactors into a solar orbit to minimize the radiation hazard.

estimates 4,000 to 5,000 kg), the Martian gravity low, and the atmosphere thick enough to provide some braking, the rockets used would not have to be particularly powerful or efficient. The landing of a 70,000 kg habitat on Mars, on the other hand, would require rockets with significant thrust and tens of thousands of kg of fuel, in addition to a parachute braking system. Either storable or cryogenic chemical-fueled rockets could be used; cryogenic fuels would produce higher exhaust velocities, but significant development of cryogenic fuel storage technology would be needed to store such fuels for the duration of a journey to Mars.

VII. Evaluation of Russian Hardware in the SEI

Evaluating individual items of Russian space hardware to determine their suitability for use in in the SEI requires that each item of hardware be judged against technical, economic, and policy criteria. These criteria are:

- Capability to satisfy the technical requirements of the SEI,
- Difficulty of integration into the SEI,
- Comparative cost to alternative hardware or technologies,
- Availability within the requisite time frame,
- Political implications of use in the SEI, and
- Potential additional benefits to U.S space efforts.

Some of these criteria are more complex than they may appear to be at first glance. For example, the first criterion must take into account not only the hardware's current capability to satisfy the technical requirements of the SEI, but also its potential for modification to meet those requirements. The comparative cost criterion must often measure the Russian hardware not only against any U.S. or internationally available equivalent, but also against potential development programs that could produce such an equivalent, and even against completely different technologies that might meet the SEI's requirements. Finally, the criterion of potential additional benefits, which would generally only apply to cooperative development programs, requires that the Russian hardware be examined in the context of its possible use elsewhere in the U.S. space program.

Energia Launch Vehicle

The Energia launch vehicle is an attractive option for fulfilling the SEI's lunar and Martian heavy-lift requirements. The minimum requirements for lunar missions were that the rocket be available by the early years of the 21st century and that it have the capability to deliver payloads of at least 60 metric tons to LEO. For Mars missions, the required launch capacity will probably be considerably larger, but the capability will probably not be needed until after 2010.

The current version of the Energia is able to deliver 88,000 kg into a 200 km altitude orbit at an inclination of 51.6°; modified versions should be able to deliver 200,000 kg to the same orbit.[208] This exceeds the SEI's hardware requirements as long as the mission plan allows the payload to be delivered into an orbit with an inclination greater than 45°. Direct lunar missions, for example, would not be greatly affected by the use of such a high inclination parking orbit, though such an orbit does render completely in-plane transfers to the Moon impossible. Most SEI heavy lift payloads, however, will involve assembly in orbit. If these missions involved an Energia launched from Baikonur, the assembly would have to take place in a high inclination orbit, as the Energia payload capacity is rapidly reduced for low-inclination orbits (it can only deliver about 30,000 kg to a low 28.5° inclination orbit).

One possible means of solving this problem would be to perform the assembly in a high inclination orbit (which would slightly lower the payload capacity of launch vehicles traveling to the orbit from lower latitude launch sites); another would be to launch the Energia from a lower latitude launch

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[208]Steven J. Isakowitz, International Reference Guide to Space Launch Systems, American Institute of Aeronautics and Astronautics, 1991, p.119.

site. The latter idea would require the construction of a new launch pad and assembly building, but the concept is not totally infeasible, as the Energia can be delivered anywhere in the world on the An-225 transport aircraft,[209] and does not require vast amounts of payload integration due to its horizontal stacking and side-mounted payload design.

The alternatives to the Energia as the SEI's heavy-lift vehicle are all development programs, as the Energia is the world's only currently available heavy-lift vehicle. Only one of these development programs, the New Launch System (NLS) is currently underway. The NLS program is basically a rocket engine development program, but it could result in the production of a heavy-lift vehicle, the NLS-1, which would have a LEO payload capacity of 60,000 kg. The future of the NLS program, particularly the heavy-lift portion, is in serious jeopardy,[210] however, as its price tag is estimated at $15 billion through 1995. Other possible competitors to the Energia include a version of the space shuttle that carries a payload instead of an orbiter, and a new launch vehicle using technology (particularly the rocket engines) from the Saturn V program.[211] It is a very safe guess that any of these development efforts would cost billions of dollars. While the price of an Energia (quoted at $110 million in 1990)[212] may rise, it will certainly not approach that level.

The most serious problem with the use of the Energia as the SEI's heavy-lift vehicle is that it may no longer be available by the time it will be

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[209] Korchagin, V., "Buran Flies to Baikonur", Sotsialisticheskaya Industriya, November 20, 1988.

[210] Leonard David, "House Panels Urged to Back Smallest of NLS Boosters", Space News, March 30-April 5, 1992.

[211] Synthesis Group on America's Space Exploration Initiative, America at the Threshold: America's Space Exploration Initiative, U.S. Government Printing Office, Washington, 1991, p.65.

[212] Steven J. Isakowitz, International Reference Guide to Space Launch Systems, American Institute of Aeronautics and Astronautics, 1991, p.108.

needed. The Energia has not been launched since 1988, and there is no apparent demand for its services within Russia (though its designers at NPO Energia have been attempting to create such a demand).[213] As the time since its last launch increases, the chance that the program can be successfully restarted will begin to decrease. Perhaps an even larger problem is that the Energia's strap-on boosters are manufactured in the Ukraine, and its only existing launch site is in Kazakhstan. In the Energia's favor, though, it has the powerful NPO Energia organization behind it, and it has unique capabilities, which the Russians may not want to give up.

The use of the Energia in the SEI would probably not be strongly opposed. (As discussed in Chapter IV, the means by which the vehicle was used would have a strong effect how its use would be received.) As the Energia has no existing equivalent, opposition from the U.S. aerospace industry would be muted, coming mainly from companies with hopes of developing a U.S. heavy lift vehicle. United States defence interests could also possibly intervene, since the Energia's strap-on boosters are produced in a factory that used to double as the Soviet Union's largest ICBM factory. This plant however, has announced that it is ceasing military production,[214] so this issue may be irrelevant by the time frame of the SEI. Finally, there would likely be virtually no opposition within Russia to the use of the Energia in the SEI.

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[213]V. Nelyubin, "King of Satellites; Another 'Project of the Century'", Komsomolskaya Pravda, February 15, 1991.
[214]Moscow Radio Rossii Network, 1200 GMT, March 2, 1992.

Robotic Precursor Missions

Another potential Russian contribution to the SEI might be the provision of robotic precursor spacecraft and the boosters to launch them with. Russian robotic spacecraft, with either Russian, U.S., or international scientific instruments on board could potentially be used for both lunar and Martian precursor missions; Russian rockets could be used to launch either Russian or U.S. spacecraft to the Moon and Mars.

Two Russian missions to Mars are already in development. The Mars '94 mission, scheduled for a 1994 launch on a Proton booster, will include an orbiter, two small meteorology stations, and two sub-surface penetrators. The Mars '96 mission, which would also be launched on a Proton, may include one or more rovers and an instrumented balloon. The Mars '94 program has recently been in turmoil; without the support of the European nations participating in the mission, it would probably have been delayed or cancelled.[215] Some in Russia are still extremely doubtful that it will get off the ground in 1994,[216] and the viability of the Mars '96 mission is even more uncertain.

Apart from these two missions, any Russian spacecraft contributed to the SEI would be new; although they could draw on previous designs, they would require building mostly new hardware. Some indication of how successful the new missions are likely to be can be gained form examination of the historical success rates of similar missions. This examination makes it clear that the Russians, at least historically, have had fairly good success with

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[215]Peter B. deSelding, "French Agree to Prop up Mars Missions With Cash", Space News, February 17-23, 1992.
[216]Yaroslav Golovanov, "Just Where Are We Flying To?", Izvestia, December 17, 1991.

robotic lunar exploration, but have had a truly dismal record in their attempts to reach Mars.

The Russians have already successfully carried out a wide range of lunar precursor missions. While they did not always initially meet with success, the Soviets were eventually able to put a series of orbiters around the Moon and successfully land other spacecraft on the Moon's surface. Among the Russian spacecraft landed on the Moon were the Lunokhod rovers, the only robotic lunar or planetary rovers ever successfully used, and the Luna spacecraft, the only successful robotic sample return mission. In contrast, out of a total of 16 attempts to reach Mars, the Soviets have never had a complete success--most of the missions were total failures. The primary cause of the failures is believed to be that the Russian space program is unable to achieve the long-duration reliability that is needed to carry out robotic Mars missions.

Even though the Russian's have historically had success in conducting lunar orbiter and rover programs, their lunar rovers and orbiters probably would not be as capable as equivalent U.S. spacecraft. First, Russian scientific instruments are generally not up to Western standards--this is demonstrated by the extensive use of European instruments on recent Russian spacecraft. Second, Russian miniaturization and computer technology is not up to U.S. standards; for this reason they would probably be unable to produce autonomous rovers or mini-rovers.[217]

Russian launch vehicles, on the other hand, are quite capable of meeting the requirements of delivering robotic precursor spacecraft to their targets. The three Russian launch vehicles (actually two Russian and a Ukrainian) that might be used for such a task in the SEI are the Molniya, the

[217]Polsky, Debra, "JPL Proposes Small, Cheap Mars Landers", Space News, March 2-8, 1992.

Proton, and the Zenit-3. The Molniya launch vehicle is capable of delivering 1600 kg payloads into a lunar transfer orbit and about 700 kg into a low-energy Mars transfer. While this may be too small for some SEI hardware needs, the Proton booster would probably be able to launch any SEI precursor mission, as it is able to deliver a 5,700 kg payload into a lunar transfer orbit and 4,600 kg into a Mars orbit. The Zenit-3 launch vehicle, if it were ever produced, would also probably have the necessary launch capacity to launch any SEI precursor. Both the Molniya and the Proton have reliability levels comparable with Western launch vehicles; the Zenit-3 has never flown.

Integration of Russian robotic missions into the SEI would not be particularly difficult, mostly because the precursors are not operationally linked with the rest of the SEI. If Russian launch vehicles were to launch Russian satellites the integration problem would be reduced to ensuring that the U.S. deep space communications network was able to communicate with the spacecraft. Use of U.S. instruments on Russian spacecraft and Russian instruments on U.S. spacecraft would also not be particularly difficult, as there is considerable experience with this type of integration. Finally, even the use of Russian launch vehicles to launch U.S. satellites would not be a particularly difficult integration task, especially once the Russians gain experience in launching foreign satellites on a commercial basis.

The relative costs of using Russian and U.S. hardware in the SEI's precursor missions will, as was discussed in Chapter IV, depend strongly on the method of cooperation between the U.S. and Russia. In general, though, developing a new Russian spacecraft would probably be less expensive than developing an equivalent U.S. spacecraft. The problem is that the Russian spacecraft would probably also be less reliable and less capable than its U.S. equivalent. Russian boosters would also probably be less expensive than their

U.S. counterparts; their reliability and capabilities however, would probably be very similar to those of U.S. launch vehicles.

It is not certain that the Soviet launch vehicles will be available in the time frame (roughly from the late 1990s to 2005) they would be needed to launch SEI precursor missions. The less powerful Molniya spacecraft seems fairly likely to survive, as it is a derivative of the same "A-class" launch vehicle that is the most commonly used Russian rocket. In addition, the Molniya can be launched from either Baikonur or the Russian launch site at Plesetsk. The Proton, on the other hand, can currently only be launched from Baikonur, which is in Kazakhstan. The Proton is also notoriously environmentally unfriendly, which may jeopardize its future at Baikonur. The Proton is fairly crucial to the Russian space program, though, as it is used to launch space station modules, so it seems likely that it will also be preserved.

There are few political implications inherent in using Russian robotic precursor spacecraft or scientific instruments in the SEI, but the use of Russian launch vehicles could cause some trouble. Launching Russian satellites on Russian launch vehicles would not cause much trouble in the U.S., but using Russian launch vehicles to launch U.S. spacecraft would certainly arouse strong opposition from the U.S. aerospace industry. In the same vein, launch of Russian spacecraft on U.S. launch vehicles might be opposed by the Russian space industry.

In summary, Russian spacecraft will probably be capable of carrying out lunar missions, and Russian launch vehicles will probably be available to launch those missions. Russian lunar spacecraft, though, may need U.S. instruments to fulfill SEI data gathering requirements. Finally, launch of U.S. robotic spacecraft on Russian launch vehicles, while feasible, carries a degree of risk due to the uncertainty within Russia, and could arouse opposition within the United States.

Mir Modules as SEI Habitats

It is theoretically possible to use a Soviet space station module as a lunar or Martian surface habitat or as a Earth-Mars space transfer habitat. While this initially seems an intriguing concept, problems arise that may make it infeasible. First, it must be understood that the current Mir station could not be used for these tasks, as it will have long exceeded its operational lifetime by the time it would be needed for use as a habitat. A new Mir duplicate, or even a modified Mir will not be appropriate for these missions either, though, as the requirements for operating in LEO have resulted in the design of a habitat that is not suited for meeting the requirements for use either on a planetary surface or in deep space.

The primary problem for almost any use of a Russian space station module as an SEI habitat is the issue of radiation protection. Russian space stations do not have any radiation protection, relying instead on the shielding provided by the Earth's magnetic field.[218] This means that the entire space station module would need to have shielding added for any use in space or on the Moon; even for a short-term habitat, a radiation proof "storm shelter" would be needed. Use on the Moon would also require a different power system, as the photovoltaic/battery systems used in Earth orbit would not be appropriate for the long-duration lunar eclipse.

As radiation requirements rule out the use of a space station module in deep space and on the Moon, the only real opportunity left would be to use

[218]Moscow Tass in English, 2036 GMT, October 26, 1989.

the module as a Mars habitat. In this case too, though, numerous changes would be necessary. First, the space station modules would have to be redesigned internally so that the astronauts could function inside them in a gravity field. The effect of gravity may also have some unexpected effects on the module's subsystems. Finally, the capability of the module to land on Mars is uncertain, and would have to be examined.

The overall problem with using a Russian space station module as a habitat elsewhere in the solar system is that the Russian space stations are the result of years of optimization for use in the particular environment of LEO. It would probably be simpler and more efficient to design entirely new habitats for use in deep space or on planetary surfaces than to modify the Russian space station design.

Use of Mir to Prepare For the SEI

While the Mir space station may be inappropriate for use as a SEI habitat, it could potentially be very useful in the preparatory phases of the SEI. As it is clear that more life science data is needed before long-duration SEI missions can be conducted, one preparatory use of Mir might be as a laboratory for conducting long-term life science experiments.

The only other location at which such experimentation could be be conducted would be on board the U.S. space station. If a U.S. space station is built, it would probably be the optimum place to conduct SEI life sciences experimentation, because it would have more power and a better microgravity environment than the Mir station. This is one case, though, where the existence of the Russian hardware may be more assured than the equivalent U.S. hardware, as the U.S. space station is perennially in danger of cancellation or radical redesign.[219] If the U.S. space station is severely delayed or cancelled, Mir will become the most viable option for a pre-SEI life sciences laboratory.

It seems fairly likely that the Mir program will continue to exist for at least the next few years. One factor that may aid in its survival is that Russia has made plans with the U.S. and with European nations to conduct joint programs involving Mir over the next few years. In addition, the Mir program is still the most prestigious part of the Russian space program, and Mir is one of the few Russian space projects that is regularly bringing in hard currency. One event that could cause the early end of the Mir program might be the death of a cosmonaut--such an event becomes more likely as Mir ages and the cosmonauts on board perform ever more risky extra-vehicular activities.

There would be many problems associated with using the existing Mir station for space life sciences research, many of them due to the fact that the existing Mir station has already been in space beyond its initial design lifetime. Currently, astronauts on Mir have very little time to conduct research, because 80% of their time is spent on life-support issues, including repairs, freight handling, and exercise.[220] These problems would be reduced, but certainly not eliminated,if a new Mir were sent up.

The U.S. could conceivably acquire a dedicated Mir-type module for use as a life sciences laboratory in LEO, but, in addition to the problems described above, the integration of the station into the U.S. space infrastructure would be very complex. Use of a Mir-type space station would also probably tie the

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[219]Liz Tucci, "Goldin Orders Station Revision", Space News, August 17-23, 1992.
[220]Yaroslav Golovanov, "Just Where Are We Flying To?", Izvestia, December 12, 1991.

U.S. to using a Proton launch vehicle to put the station in orbit, and Soyuz launch vehicles and capsules, as well as Progress capsules, to resupply it. The problem is the Mir is not just a single hardware item, but a system composed of many hardware elements. Either the U.S. would have to use those elements or redesign the station for use with the U.S. space infrastructure. Overall, it would probably be more cost effective to design and build a simple station compatible with the U.S. space infrastructure to serve as a life sciences laboratory than to buy a Russian station.

Perhaps a better way to utilize Mir and its descendants in the SEI would be to use them to learn from the two decades of Russian long-duration space habitat experience. Experience learned from the Mir program could allow the U.S. to avoid problems experienced by the Soviets as they developed their long-duration space capability. In addition the technology that has been developed over the years to support the Russian space stations could be transferred for use in the SEI. An example of such a technology would be Mir's fourth generation life support system, which includes a unique debugged system for extracting water from the atmosphere.[221]

Political problems with the use of Mir for life sciences experimentation or technology transfer would be directly linked to the possible effect that such use might have on the U.S. space station. If the U.S. space station is either cancelled or built, these problems should be fairly small--it is only when the U.S. station is on the edge of cancellation that its supporters will oppose anything that might threaten it. Any reaction inside Russia to U.S. use of Mir

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[221]Ravil Zaripov, "Lemons for the Funeral Repast, or 'Space Games' of the CIS", Moskovskiy Komsomolets, January 17, 1992, in JPRS Report Science and Technology - USSR: Space, April 1, 1992.

is likely to be positive, unless the use is so pervasive that the U.S. is seen to be "taking over" Mir.

Nuclear Thermal Rocket

Human exploration of Mars becomes much more difficult without a nuclear thermal rocket for propulsion between the Earth and Mars. While the U.S. is still years away from even testing such a rocket, the Russians have already fired a nuclear thermal rocket for durations of one hour with exhaust velocities of 8,820 m/s and a thrust of 20 kN. While this is on the low side of the SEI requirements, it seems likely that with some further development, the requirements could be met.

The U.S. nuclear thermal effort, which is still largely classified, has spent $130 million to date. Engine tests may be conducted as early as 1994, but they will drive the program cost up to $800 million[222] Estimates of the total cost to develop a working nuclear thermal rocket from this program were estimated at from two to five billion dollars for a first flight in 2006.[223] Though further investigation is needed, it seems quite possible that using the existing Russian nuclear thermal rocket could save on the order of a billion dollars.

There are likely to be few political problems in the U.S. with the use of a Russian nuclear thermal rocket, particularly if the U.S. acquires the technology involved. The U.S. effort to build a nuclear thermal rocket began as a DoD program to develop nuclear thermal upper stages for launch

[222]Andrew Lawler, "USAF to Lift Veil on Covert Nuclear Rocket", Space News, January 13-26, 1992.
[223]Leonard David, "Soviets Reveal Work In Advanced Nuclear Rockets, Seek to Share", Space News, September 16-22, 1991.

vehicles; as such use has become less likely, the DoD has become less interested in the program, so they would probably not fight its eclipse by the Russian program. Once acquired, nuclear thermal rocket technology could also be used elsewhere in the U.S. space program; one such use might be in enabling fast missions to the outer planets. Within Russia, the rocket's developers are anxious to work with the U.S. either in selling their technology or in developing joint projects.[224] Reportedly, their willingness to cooperate stems from a desire to keep the program alive--this means that there is no guarantee that the Russian nuclear thermal rocket will still be available in the post-2005 time frame in which it would be needed.

Topaz Thermionic Reactor

Nuclear reactors may be needed for long-term Lunar and Martian habitats and for use in nuclear electric propulsion for cargo missions. The Soviet Topaz thermionic nuclear reactor is not able to meet the SEI's requirements, but could possibly serve as the starting point for a program to develop reactors that would be able to meet the SEI requirements.

The Topaz reactors have two features that prevent their use as SEI power sources. First, they do not produce enough power. The approximate power output of a Topaz reactor is 10 kw; power levels of at least 50 kw would be desired for SEI habitats, and multi-megawatt power is needed for the SEI's electric propulsion needs. Second, they do not have very long lifetimes; the longest duration which one has been used in space has been a year. The long-duration SEI habitats would optimally use reactors that lasted reliably over

[224]Leonard David, "Soviets Reveal Work In Advanced Nuclear Rockets, Seek to Share", Space News, September 16-22, 1991.

several long-duration missions, and a nuclear electric rocket would probably also be better served by a more durable reactor, which would allow it to make multiple journeys.

The major alternatives to using the Topaz reactor in the SEI would be either to use a U.S. thermoelectric reactor based on the SP-100 program, or to not use nuclear reactors at all. The only major effect on the SEI of nuclear reactors not being available would be that it would be difficult to provide power for large bases, and less efficient propulsion would have to be used for the transport of cargo between the LEO and orbits around Mars and the Moon. It would not mean the end of the SEI, however. If nuclear power is going to be used, the major alternative to the Topaz is the SP-100, a NASA/DoE/DoD program to develop a space thermoelectric reactor.[225]

The major advantage that thermionic reactors have over thermoelectric reactors is that they will not have to be as large to produce the same amount of power. Estimates are that thermionic reactors will have four to six times smaller radiators and will be two to three times more efficient than thermoelectric reactors.[226] As power levels increase, the mass advantage of thermionic reactors becomes larger, because at high power levels the radiator becomes a very large fraction of the total reactor mass.

The principal advantage of the Topaz reactor over the SP-100 system, though, is that it has actually been built and flown in space, while the SP-100 is still a development program. Recent estimates are that the SP-100 is still a billion dollars and anywhere from 10 to 18 years away from a flight

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[225]Philip Pluta, et. al., "SP-100, a Flexible Technology for Space Power From 10s to 100s of Kwe", Proceedings of Space Manufacturing 7, AIAA/SSI Conference at Princeton, NJ, May 1989.
[226]Synthesis Group on America's Space Exploration Initiative, America at the Threshold: America's Space Exploration Initiative, U.S. Government Printing Office, Washington, 1991, p.70.

demonstration.[227,228] The use of a Topaz reactor is likely to be opposed by some supporters of the SP-100; on the other hand, the DoD may be interested in the thermionic system because its smaller size could ensure its survivability. Finally, as the Russians have already turned this technology over to the U.S. strategic defense initiative office, it is unlikely that they would protest against its use in the SEI.

Chemical Rocket Engines

In addition to the possible use of Russian nuclear thermal rocket engines, it might also be worthwhile to use Russian chemical-fueled rocket engines in the SEI. Most conventional Russian rocket engines do not have performance characteristics that would make them worth integrating into U.S. spacecraft. The two clear exceptions are the RD-170 engine used in the Zenit and Energia launch vehicles, and the small SPT-70 and SPT-100 electric thrusters. As the electric thrusters have already been transferred to the United States,[229] this sub-section will concentrate on the use of the RD-170.

The RD-170 rocket engine is the most powerful liquid fueled-rocket engine in existence. Its probable use in the SEI would be as the basis for a heavy-lift vehicle. Such use would be a compromise between using an Energia and not using any Russian technology; both the risks and benefits would be reduced. One additional benefit that would be gained by the use of the RD-170 in the SEI, though, is that it would probably result in technology

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227Vincent Kiernan and Andrew Lawler, "Administration Pits Soviet Topaz Reactor Against SP-100", Space News, January 13-26, 1992.
228Vincent Kiernan, "Nuclear Technologies Vie as Space Power Source", Space News, March 4-10, 1991.
229Daniel J. Marcus, "Russia's Satellite Thrusters Draw NASA, Defense Scrutiny", Space News, April 13-19, 1992.

transfer to the United States. Use of the RD-170 would probably have very little opposition in the U.S., particularly if the technology were transferred to U.S. firms. Opposition in Russia might exist, but would be muted, especially if Russian firms were involved in the development of the SEI heavy-lift vehicle.

The major competitors to the RD-170 as the possible engines for a new heavy-lift vehicle would be the engines that are being developed in the NLS program and a revived version of the F-1, the rocket engine used in the Saturn V launch vehicle. The cost of the NLS program and the uncertainty about it ever developing a heavy-lift vehicle have already been discussed. The F-1, though, might represent a more serious competitor to the RD-170. The Synthesis group suggested that the use of F-1's in the SEI might allow for a faster, cheaper, and safer heavy-lift launch vehicle.[230] The F-1 is not as capable as the RD-170, however, as it has less thrust, a lower exhaust velocity, and less throttling capability. It is also unclear how much the revival of the F-1 would cost, but it could be very expensive, as the engine's supplier base is gone and manufacturing technology has changed greatly since the early 1970s, when it was last produced.

While it appears that the RD-170 might be a leading candidate for use in the development of an SEI launch vehicle, its continued production is not assured. The RD-170 is produced by NPO Energomash, which is in Russia, but its only use is in the Zenit launch vehicle and the Energia strap-ons, which are produced at NPO Yushnoye, in the Ukraine. If the Energia and Zenit programs were to be cancelled, or forced to end because of

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[230]Synthesis Group on America's Space Exploration Initiative, America at the Threshold: America's Space Exploration Initiative, U.S. Government Printing Office, Washington, 1991, p.65.

disagreements between Russia and the Ukraine, the capability to produce RD-170 might erode over the next few years.

VIII. Recommendations

There is not one clear "best" way to use Russian space hardware in the SEI. Though particular hardware items can be identified as being able to meet SEI requirements at low cost, the choice of an optimal strategy for using the hardware will depend on the chooser's opinions on the worth of the SEI, on the value of cooperation with Russia, and on appropriate levels of risk-taking. For this reason, two different strategies are proposed for the use of Russian space hardware in the SEI.

The first strategy is a fairly low-risk approach that, in most cases, utilizes Russian space hardware only as a basis for U.S. technology development efforts. This strategy is designed to reduce the cost of the SEI, but not to promote the initiative, and to reap the available benefits of the Russian space program without attempting to preserve its capabilities. The second strategy is a higher risk approach that would involve more use of Russian hardware and broader U.S./Russian cooperation. As well as having the potential to sharply reduce the costs of the SEI, this strategy could also increase the prominence of the initiative in the United States and help preserve some Russian space capabilities useful to the SEI. Rather than avoiding uncertainty, this strategy would attempt to take active steps to reduce it.

A Low-Risk Strategy for Using Russian Space Hardware in the SEI

In this strategy, the U.S. would attempt to gain the maximum benefit from Russian space hardware without relying on the unstable Russian space program or committing the nation to pursuing the SEI. This plan thus involves no large scale cooperative activities and no pledges to use Russian space hardware in the SEI. Instead, it concentrates on the immediate use of Russian space hardware as the basis of U.S. technology development programs. In addition, it does not discourage small-scale scientific cooperation between Russian and U.S. space scientists.

The major elements of the low risk strategy are:

- Purchase of a Russian nuclear thermal rocket and necessary technical support. The technical support could include hiring Russian researchers working on nuclear thermal rockets and using Russian nuclear rocket test facilities. The goal would be to use the knowledge gained to support a U.S. nuclear thermal rocket development program.

- Purchase of an RD-170 rocket engine and necessary technical support. The goal would be to determine whether a U.S.-licensed version would be worth developing, or, if not, whether some of the technologies involved might be useful in the NLS program.

- Cooperation with U.S. agencies already investigating the Russian Topaz-2 reactor. The objective would be to compare the ability of thermionic reactors based on the Topaz and thermoelectric reactors produced in the SP-100 program in meeting SEI requirements. Later decisions on reactor development would await better definition of the SEI.

- Scientific cooperation on Russian planetary probes. U.S. scientists would not be prevented from placing instruments on the Russian

Mars '94 and Mars '96 probes. The choice of whether or not this should be done would be made in the usual process of allocating space science resources.

- Coordination and data exchange with Russian scientists performing life science experiments on Mir. The objective here would be to maximize the useful data return from Russian experiments. Some small U.S. experiments might also be conducted on Mir; again this would be carried out through normal scientific channels.

- Encouragement of U.S. space station contractors to subcontract with KB Salyut to review space station plans and to purchase Russian space station-related technology where appropriate. The objective would be to gain from the Russian experience in designing and operating space habitats

- A 1995 reassessment of the use of Russian space hardware in the SEI. By this time, both the situation in Russia and the status of the SEI may have stabilized, thus reducing the risk of engaging in U.S./Russian cooperative programs within the SEI. As SEI missions will probably not begin until the late 1990s, 1995 will probably not be too late a date to incorporate Russian hardware into the initiative.

A Higher Risk Strategy for Using Russian Space Hardware in the SEI

The second strategy for using Russian space hardware in the SEI differs from the first in that rather than avoiding the problems associated with uncertainty, it actively seeks to reduce the uncertainty. In this strategy, the U.S. would seek to sign a high-level agreement with Russia on long-term cooperation in the SEI. Cooperative activities would start with small, trust-building exercises and work up to fairly close cooperation. While this approach features greater risks than the first approach, it could also result in greater benefits.

Rather than waiting and seeing whether the U.S. will go ahead with the SEI and what Russian hardware capabilities will survive the current troubles, this strategy seeks to influence the outcome in both countries. In the U.S., the high-level cooperative agreement would hopefully give Congress a reason to begin funding the SEI. In Russia, it would optimally provide an incentive for the government to attempt to preserve hardware items that could be used in the SEI.

Despite the long-term focus of the SEI, prompt action may be required to make this strategy work. There is no particular hurry in the U.S., but two time constraints are at work inside Russia. First, Russian space capabilities are being steadily eroded as the space program shrinks--if the U.S. waits too long, some capabilities may be lost. Just as important, the Russians are currently attempting to set goals and priorities for their space program; at a later date it may be more difficult to influence the direction of their space program.

The major elements of the higher risk strategy are:

- Having the U.S. and Russian Presidents sign an agreement to pursue long-term cooperation in the SEI. This agreement would mention the elements of the strategy listed below. The European and Japanese space agencies would also be asked to participate in the SEI.

- Adopting a strategy of slowly expanding U.S. Russian cooperative activity in the SEI, starting with small cooperative endeavors and eventually building up to the use of Russian hardware in important SEI roles.

- Designating the U.S. Mars Observer and the Russian Mars '94 missions as the initial elements of the new, cooperative SEI. If possible, some SEI-related U.S. instruments would be included in the Mars '94 mission.

- Initiation of a cooperative U.S./Russian research program on nuclear thermal rockets, using Russian nuclear rocket test facilities. The goal would be to develop and test a high performance nuclear thermal rocket for use in the SEI.

- Signing an agreement to use the Energia as the heavy-lift vehicle for the SEI, with the intent of preserving the Energia until it is needed. Other means of preserving the Energia might include finding other payloads (such as a redesigned space station) for it to launch and encouraging the Ukraine to continue manufacturing the Zenit, at least in its form as the Energia's strap-on booster.

- Cooperation with U.S. agencies and Russian designers in the study of the Russian Topaz-2 reactor. The initial objective would be to compare the ability of thermionic reactors based on the Topaz and thermoelectric reactors produced in the SP-100 program in meeting SEI requirements. Later decisions on reactor development would await better definition of the SEI.

- Assisting the Russians in carrying out life sciences experimentation on Mir. This would include providing them with the same equipment used in U.S. life sciences experiments and continuing ongoing data exchange programs.

- Hiring Russian space station designers to aid in habitat and space station design. Where necessary, Russian space station-related technology would be incorporated into the design. The objective would be to gain from the Russian experience in designing and operating space habitats.

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