NASA SP-509
VOLUME 4

SPACE RESOURCES

Social Concerns


DAVIDSON

Frontispiece

Advanced Lunar Base

In this panorama of an advanced lunar base, the main habitation modules in the background to the right are shown being covered by lunar soil for radiation protection. The modules on the far right are reactors in which lunar soil is being processed to provide oxygen. Each reactor is heated by a solar mirror. The vehicle near them is collecting liquid oxygen from the reactor complex and will transport it to the launch pad in the background, where a tanker is just lifting off. The mining pits are shown just behind the foreground figure on the left. The geologists in the foreground are looking for richer ores to mine.

Artist: Dennis Davidson

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Space Resources

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Editors

Mary Fae McKay, David S. McKay, and Michael B. Duke

Lyndon B. Johnson Space Center Houston, Texas

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Preface

Space resources must be used to support life on the Moon and exploration of Mars. Just as the pioneers applied the tools they brought with them to resources they found along the way rather than trying to haul all their needs over a long supply line, so too must space travelers apply their high technology tools to local resources.

The pioneers refilled their water barrels at each river they forded; moonbase inhabitants may use chemical reactors to combine hydrogen brought from Earth with oxygen found in lunar soil to make their water. The pioneers sought temporary shelter under trees or in the lee of a cliff and built sod houses as their first homes on the new land; settlers of the Moon may seek out lava tubes for their shelter or cover space station modules with lunar regolith for radiation protection. The pioneers moved further west from their first settlements, using wagons they had built from local wood and pack animals they had raised; space explorers may use propellant made at a lunar base to take them on to Mars.

The concept for this report was developed at a NASA-sponsored summer study in 1984. The program was held on the Scripps campus of the University of California at San Diego (UCSD), under the auspices of the American Society for Engineering Education (ASEE). It was jointly managed by the California Space Institute and the Lyndon B. Johnson Space Center, under the direction of the Office of Aeronautics and Space Technology (OAST) at NASA Headquarters. The study participants (listed in the addendum) included a group of 18 university teachers and researchers (faculty fellows) who were present for the entire 10-week period and a larger group of attendees from universities, Government, and industry who came for a series of four 1-week workshops.

The organization of this report follows that of the summer study. *Space Resources* consists of a brief overview and four detailed technical volumes: (1) Scenarios; (2) Energy, Power, and Transport; (3) Materials; (4) Social Concerns. Although many of the included papers got their impetus from workshop discussions, most have been written since then, thus allowing the authors to base new applications on established information and tested technology. All these papers have been updated to include the authors' current work.

This volume—Social Concerns—covers some of the most important issues which must be addressed in any major program for the human exploration of space. The volume begins with a consideration of the economics and management of large-scale space activities. Then the legal aspects of these activities are discussed, particularly the interpretation of treaty law with respect to mining the Moon and asteroids. The social and cultural issues of moving people into space are considered in some detail, and the eventual emergence of a space culture different from our existing culture is envisioned. The environmental issues raised by the development of space settlements are faced. Finally, the authors of this volume, which concludes the report *Space Resources*, propose some innovative approaches to space communities and habitats and consider self-sufficiency and human safety at a lunar base or outpost.

This is certainly not the first report to urge the utilization of space resources in the development of space activities. In fact, *Space Resources* may be seen as the third of a trilogy of NASA Special Publications reporting such ideas arising from similar studies. It has been preceded by *Space Settlements: A Design Study* (NASA SP-413) and *Space Resources and Space Settlements* (NASA SP-428).

And other, contemporaneous reports have responded to the same themes. The National Commission on Space, led by Thomas Paine, in *Pioneering the Space Frontier*, and the NASA task force led by astronaut Sally Ride, in *Leadership and America's Future in Space*, also emphasize expansion of the space infrastructure; more detailed exploration of the Moon, Mars, and asteroids; an early start on the development of the technology necessary for using space resources; and systematic development of the skills necessary for long-term human presence in space.

Our report does not represent any Government-authorized view or official NASA policy. NASA's official response to these challenging opportunities must be found in the reports of its Office of Exploration, which was established in 1987. That office's report, released in November 1989, of a 90-day study of possible plans for human exploration of the Moon and Mars is NASA's response to the new initiative proposed by President Bush on July 20, 1989, the 20th anniversary of the Apollo 11 landing on the Moon: "First, for the coming decade, for the 1990s, Space Station *Freedom*, our critical next step in all our space endeavors. And next, for the new century, back to the Moon, back to the future, and this time, back to stay. And then a journey into tomorrow, a journey to another planet, a manned mission to Mars." This report, *Space Resources*, offers substantiation for NASA's bid to carry out that new initiative.

Contents

V. ENVIRONMENTAL ISSUES

VI. INCREASING SUCCESS PROBABILITIES: ISSUES OF SPACE COMMUNITIES AND HABITATS

Synthesis of Space Activities 1985–2010*

The next 25 years will bring a new era in space development. Presidential policy confirms that the United States of America through its National Aeronautics and Space Administration is committed to the establishment of a permanent human presence in space.

Space-based resources offer new opportunities to make that goal achievable. Research into and development of space-based resources will give the nation additional scientific and economic leverage, while the involvement of more people in such space operations will improve human performance aloft and the quality of life on Earth.

The extension of human capabilities on the space frontier can be accomplished through a combination of human and automated activities. That is, by the extended presence of humans on a space station, by the use of robots at a manned lunar outpost, by automated and manned exploration of Mars, and by unmanned probes into the solar system. Such activities by 2010 provide a necessary springboard for further exploration and exploitation of space resources, such as on the asteroids and on Mars.

*This statement was prepared by faculty fellows Philip R. Harris, Carolyn Dry, Nathan C. Goldman, Karl R. Johansson, Jesa Kreiner, Robert H. Lewis, and James Grier Miller, assisted by workshop participants Ben R. Finney, Ronald Maehl, Kathleen J. Murphy, Namika Raby, Michael C. Simon, Richard Tangum, and J. Peter Vajk and consultants David G. Brin and Elie Shneour. These observations were made in 1984. Subsequent events, especially the reports in 1986 of the National Commission on Space *(Pioneering the Space Frontier)* and the Presidential Commission on the Space Shuttle Challenger Accident, seem to confirm their relevance.

A Combination of Human and Automated Activities

Secured to a strut of Space Station Freedom, a robotic construction vehicle maneuvers a sheet of thermal insulating foil at the command of an astronaut inside. The pressurized vehicle (which on dangerous missions need not be piloted) will be able to build large structures as well as perform delicate microelectronic repairs. Computers, communications equipment, lights, and cameras will be housed in its upper section; the lower portion will hold life support and electrical systems. Such a robot, piloted or teleoperated, represents the combination of human and automated activities that our group thinks will best accomplish the goals of assembling a space station, building a base on the Moon, and mounting an expedition to Mars.

Courtesy of the artist, Paul Hudson, and of the spacecraft designer, Brand Griffin

To stay on the "high ground," beginning with utilization of near-Earth resources, requires a long-term view of the benefits to humankind. Furthermore, an expanded infrastructure needs to be developed both on Earth and in space, first in low Earth orbit (LEO) and then in geosynchronous orbit (GEO). To achieve such objectives will require the development of bases at multiple locations in space, with more complexity and greater numbers and varieties of people on them.

Therefore, NASA should be encouraged in the short term to pursue the opportunities for space industrialization provided by a permanent space station and platform, as well as to develop the necessary technology and plans for a lunar outpost and possibly for an asteroid expedition. In this process, it is vital that support be given to research into ecological life support systems and ergonomics in space.

Over the long term—25-100 years—strategic planning should include taking advantage of the resources on the asteroids and on Mars, as well as unmanned exploration of other suitable locations in the cosmos.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

Phobos

This is the first Viking 1 Orbiter 1 picture of Phobos, one of the two moons of Mars. The irregularly shaped satellite is thought by many to be a captured asteroid. North is at the top of the picture, while the point of Phobos which always points towards Mars is at the lower left. The large crater near the north pole is approximately 5 km across. The diameter of Phobos when viewed from this angle is about 22 km. Only about half of the surface of Phobos facing the camera was illuminated. The low density and dark albedo of Phobos make some scientists suspect that it has the composition of carbonaceous chondrite meteorites. If so, chemically bound water should be plentiful.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

Mars

This mosaic, composed of 102 Viking Orbiter images, covers nearly a full hemisphere of Mars (the smallest observable feature is about 1 km across). The center of the scene shows the entire Valles Marineris canyon, over 3000 km long (about 10 times as long as Earth's Grand Canyon) and up to 8 km deep. A bright patch of white material in the eastern extremity of the canyon may consist of carbonates deposited in an ancient lake. Water appears to have flowed from east to west through the Valles Marineris and from south to north up the bright Kasei Vallis (not surficially connected to Valles Marineris) to the dark basin called the Acidalia Planitia at the top of this picture. The dark spots to the west are three of the Tharsis volcanoes, each about 25 km high (twice as high as Mount Everest). When these images were acquired by Viking 1 Orbiter 1 in 1980, the atmosphere was relatively dust-free. The white streaks, best seen in the lower left quadrant, and the hazes elsewhere are clouds, which probably consist of water ice. The resources suggested by the interpretation of this photomosaic—carbonates, volcanic gases, water ice—will be important in the development of a colony on Mars.

Photo: U.S. Geological Survey

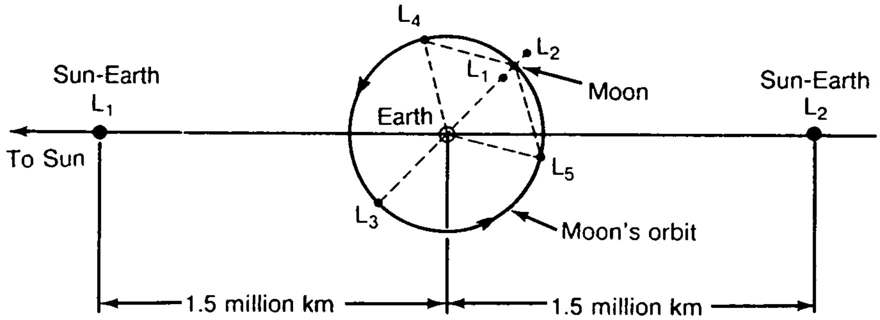
The justifications for such space activities are more than economic. They include

- Maintaining American security, leadership, and technological excellence

- The possible discovery of new resources, such as an ore body on the Moon or lunar polar ice, and of new uses for strategic areas, such as Lagrangian points (see box)

- Technology transfer to benefit global society, particularly the peoples of the Third World

Five libration points of Earth-Moon system



Lagrangian Points

There are five positions of equilibrium in the gravitational field of an isolated two-body system. (The example shown fully in the figure is the Earth-Moon system; the L1 and L2 points of the Sun-Earth system are also shown; and a third example would be the Sun-Jupiter system.) As shown by the French mathematician Joseph Louis Lagrange in 1772, these "libration points" have the interesting property that, if a third, very small body were placed at one of them with the proper velocity, the centripetal acceleration of the third body would be perfectly balanced by the gravitational attractions of the two primary bodies. Three of the Lagrangian points are situated on a line joining the two attracting bodies, while the other two form equilateral triangles with these bodies.

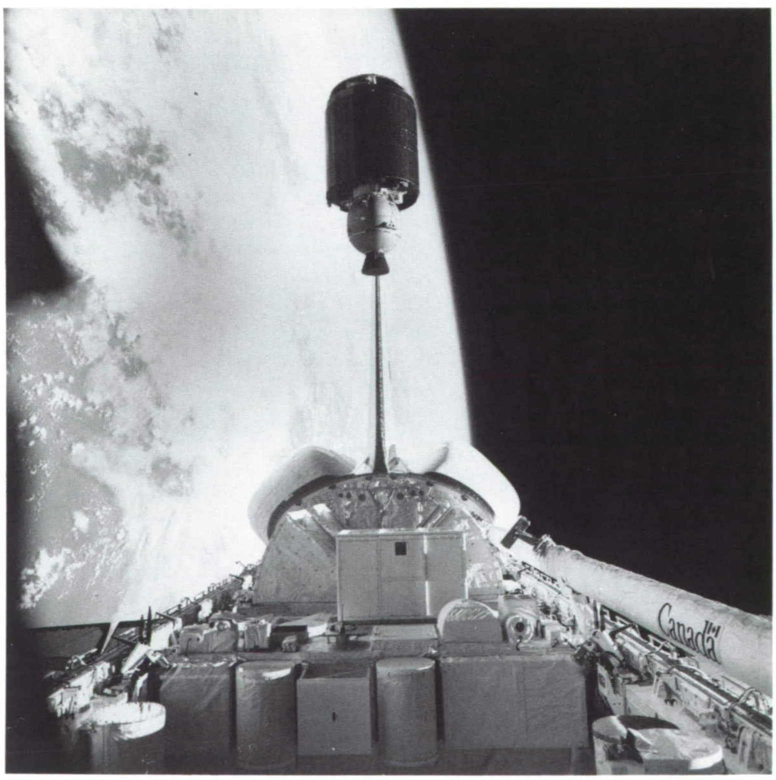
The so-called "Trojan asteroids" have been captured in the L4 and L5 points in the Sun-Jupiter system. The group of asteroids orbiting the Sun 60 degrees ahead of Jupiter have been named after Greek warriors (including Odysseus), and the group trailing Jupiter by 60 degrees have been named after warriors of Troy (including Aeneas). (Because of naming errors, there is at least one "spy" in each camp: Achilles' friend Patroclus is in the Trojan camp, and Hector, the greatest of the Trojan heroes, who killed Patroclus and was killed by Achilles, is in the Greek camp.)

This natural example and our understanding of the balance of forces at these locations lead us to consider the Lagrangian points as good places to put "stationary" satellites. Although the three collinear points are inherently unstable and the two triangular points are only quasi-stable, the station-keeping cost to maintain a spacecraft at or near one of these points for a long time is very small. A space station located at either L4 or L5 in the Earth-Moon system would require almost no fuel to keep it in place. And communication satellites located at L1 and L2 in the same system would require only small amounts of fuel for station-keeping.

Taken from Robert Farquhar and David Dunham. 1986. Libration-Point Staging Concepts for Earth-Mars Transportation, in vol. 1 of Manned Mars Missions Working Group Papers, NASA M002, June, pp. 66-77.

Economics and System Tradeoffs

The immediate rationale for extending human presence into space is primarily noneconomic—the human and scientific returns to be gained by such endeavors. Having said that, we recognize a viable market for the use of space in the communications industry. A case for investment in space industrialization has already been made by the success of commercial satellites and sensors. From parametric sensitivity analysis of the benefits vs. the costs of using space, it seems that information resources will have the most payback in the near term.



A Case for Investment in Space Industrialization

The Indonesian Palapa B communications satellite is just about to clear the vertical stabilizer of the Space Shuttle Challenger *as it moves toward its Earth-orbiting destination. The noneconomic benefits of such devices, making communication possible across undeveloped stretches of the Earth's surface, are readily apparent. So, too, are the economic benefits to the space industry which develops them. In the near term, such information resources will probably have the most payback. In the long term, the commercial prospects of energy and material resources may grow large.*

By the turn of the century, growth industries may emerge in space for materials processing, then eventually for manufacturing and mining, solar power, and other applications (see fig. 1). The Moon may prove to be economically attractive when production of oxygen, propellants, and bulk shielding materials is undertaken. The growth of human activities in space will continue to be limited by economic constraints, such as the high cost of transportation and of life support, both of which initially involve replenishment of supplies from Earth.

Since NASA is not an ordinary business but an R&D organization engaged in high-risk, high-technology, large-scale endeavors, the agency requires large amounts of up-front capital. Its financial requests should be evaluated by criteria that go beyond mere cost/benefit ratios. Although its ventures involve much risk, exposing national prestige as well as capital, NASA's space programs also require boldness because of the possible economic and other rewards to be gained by the country and the world.

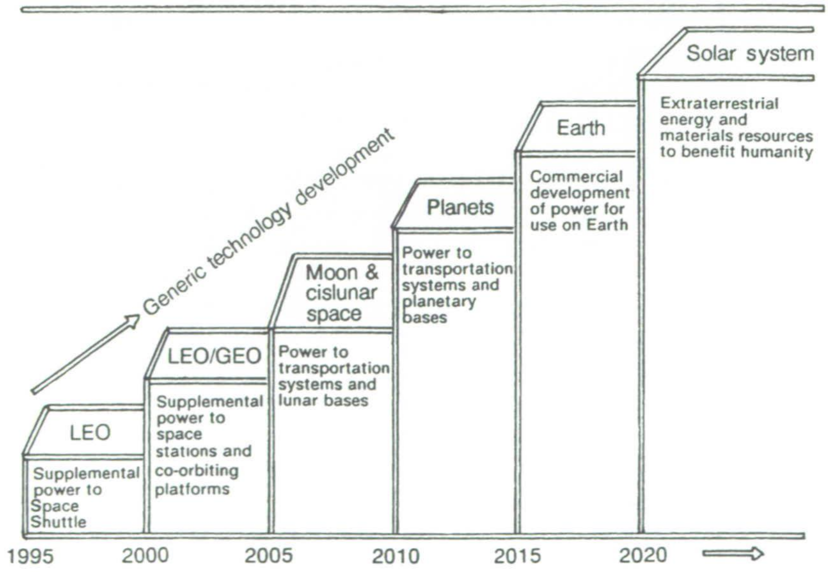


Figure 1

Growth Path for a Power Beaming Industry

Developing the capacity to beam power generated in space (from photovoltaic cells on an orbiting platform or at a lunar base) to other locations for use might become a growth industry. The power would first be beamed to space facilities only short distances from where it is generated. Later it might be beamed back to Earth or on to spacecraft moving farther out into the solar system.

Taken from Arthur D. Little, 1989, Report of NASA Lunar Energy Enterprise Case Study Task Force, NASA TM-101652, July, p. 82.

The principal system tradeoffs identified for the next 25 years are choices among (a) space transportation systems; (b) power systems in space and on the Moon; and (c) automation, human presence, or a combination of both. In attempting to develop cost projections for such purposes, NASA would be well advised to utilize new parametric models, such as the sensitivity analysis demonstrated in the 1984 summer study; it offers a method for testing and quantifying differing assumptions about space resources.

However, to create the necessary economic infrastructure for these space undertakings, new sources of income that go beyond the Federal budgeting of NASA requests are essential. New financial participation may come from tax incentives and other encouragements of space entrepreneurs and technological venturing. New legislation is desirable which facilitates space commerce and involves business on a broader basis than does the aerospace industry, while improving the insurance situation for space activities. Furthermore, new options should be carefully evaluated by the President and Congress for greater public financial participation in space endeavors that will spread the risks, such as through a national lottery, Government bonds, stock investments, or limited partnership opportunities. In such ways, the fifty existing space advocacy organizations might be mobilized, so that their collective membership of 300 000 and their aggregate annual budget of $30.5 million* would have greater impact on space development.

While NASA should be urged to pursue innovative ways to reduce the costs of its space transportation system and other operations, its budget should be increased to cover both operational commitments and new developments. Other financial benefits might come from developing technological systems that are more generic or building reservoirs of consumables onsite in space, using nonterrestrial materials when possible. Savings might be further effected by designing support systems that permit recycling and accept substitute sources or even substitute chemicals. Creative funding may involve the privatization of many space activities, so that the NASA budget can focus on research and development.

*M. A. Michaud, 1987, *Reaching for the High Frontier: The American Space Movement, 1972-84* (New York: Praeger).

Management and Structure

The next stage of space development poses a challenge for the management of large-scale technical enterprises, such as a space station and a lunar outpost. In this regard, we recommend that the nation's political leadership consider giving NASA a new charter—one that would allow it greater autonomy and flexibility (like the Tennessee Valley Authority). Perhaps all NASA's research functions should be concentrated into a National Institute of Space.

In this postindustrial information society, human systems like NASA are expected to go through a process of organizational renewal. Since NASA made management innovations during the Apollo period, it can capitalize on this heritage to meet the challenges of change in organizational culture and in the role of management, especially as a result of advances in management information systems (MIS). More behavioral science management research is also needed on (1) the role of, problems faced by, and skills required of space project leaders (both those who manage space resource undertakings from Earth and those who lead space programs onsite) and on (2) the macromanagement approaches required for effective administration of large-scale technological projects in space.

Legal, Political, Social, and Environmental Issues

Technological excellence in space will not only serve the needs of national pride, defense, and growth but also ensure America's leadership, especially in high technology and its applications. To energize the nation's will toward space development requires the creation of mechanisms such as the following, which we recommend to the nation's leaders for consideration:

- Foster a national consensus on our space goals by encouraging greater public involvement. The means might be a White House conference on space industrialization, town meetings or teleconferences, interagency forums on Government and military activities in space, a space congress of trade and professional associations on their roles in space, a convocation of space organizations and interest groups on NASA's needs and plans, space conferences for media representatives, a NASA summer study for artists and dramatists, and more educational programs on human migration into space. The International Space Year of 1992, the 500th anniversary of Columbus' landing in the Americas, might prove a suitable focus for such citizen participation in our country's space program.

- Foster the legislative environment and incentives that would encourage the private sector in space commercial enterprises. The means might be joint ventures with NASA, corporate consortia for space projects, Federal space insurance, and contracting outreach beyond the aerospace companies (e.g., into the robotics and automation and other high-technology industries).

- Foster international opportunities by NASA for joint endeavors with other national space agencies, both with allies and possibly with the U.S.S.R. The Apollo-Soyuz mission (see fig. 2) offers a precedent for creating peaceful space synergy. Much yet remains to be done in the utilization of space resources both for healthy competition and for international cooperation. Perhaps we should consider participating in an international mission to Mars.

Figure 2

Crewmembers of the Apollo-Soyuz Test Project Visit With President Gerald R. Ford

President Ford holds the Soyuz part of a model depicting the 1975 Apollo-Soyuz Test Project, an Earth orbital docking and rendezvous mission in which Americans and Soviets cooperated. With the President are Vladimir A. Shatalov, cosmonaut training chief; Valeriy N. Kubasov, flight engineer; Aleksey A. Leonov, crew commander; and Thomas P. Stafford, crew commander; Donald K. Slayton, docking module pilot; Vance D. Brand, command module pilot. Dr. George M. Low, NASA's Deputy Administrator, is behind President Ford.

Overall Desirabilities and Probabilities

Space is a place to motivate new modes of human cooperation. [The National Commission on Space (1986) offered specific recommendations in this regard.]

An imaginative plan for a lunar base might inspire the next generation to turn outward in pursuit of challenges on the next frontier. Space resources are vital for the development of human habitats and factories, be they on the Moon, on asteroids, or on Mars.

In the long run, human migration into space will not only alter our own human culture on Earth but also result in the creation of a new culture adapted to the realities to space living. Apollo 11 broke our perceptual blinders that we were Earthbound and opened up to us the possibilities for exploring and utilizing the universe. To prepare for the ever-expanding human presence in space, we need more study of

- Space ecological and life support systems by biochemists, microbiologists, research physicians, and other scientists. New policies will be needed on space ecology and the use of resources on the "high frontier."

- Design and construction at both the space station and a lunar base of a laboratory for the medical, chemical, biological, and psychological monitoring of the human inhabitants. A data bank could be developed for analysis of information on the human condition in long-term space living.

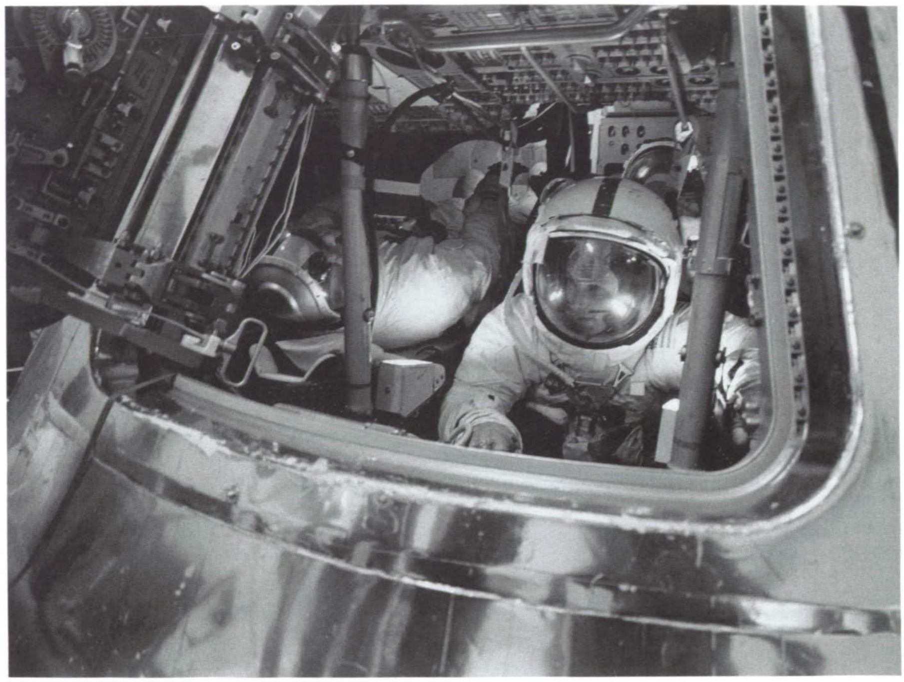
- Space ergonomics to obtain human-factor data and designs that will enhance the quality of life in a confined space environment and will reduce discomfort while people are engaged in space travel. Special attention should be directed to the human/machine interface and to the prolonged use of life support or safety systems.

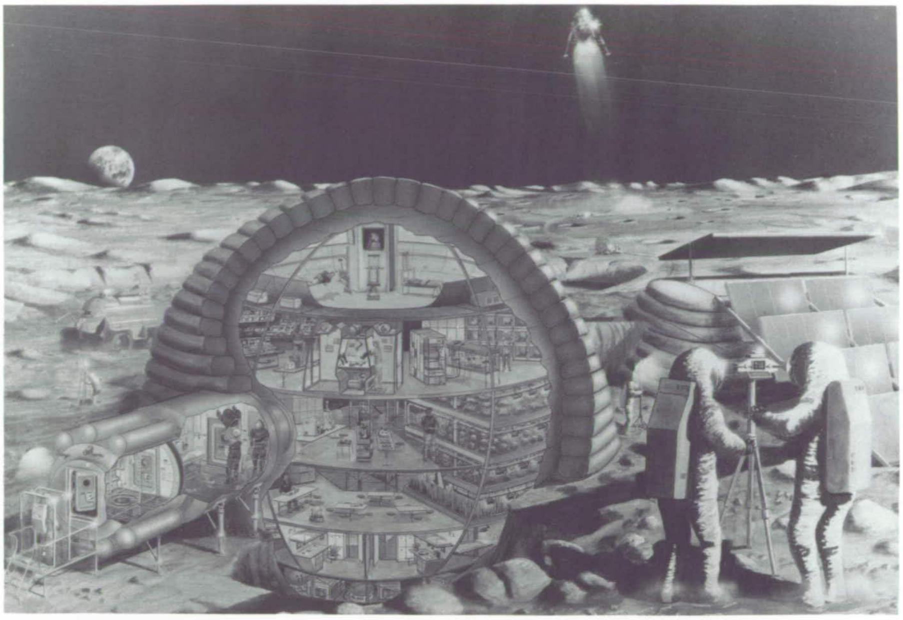
- Space habitat architecture that requires new concepts and materials. The latter will involve availability, end use, dual utilization, recycling, and substitutions. New processing techniques will be created that are suitable for the space environment.

- General living systems theory and planning that can contribute to the mapping out of human activities on the space station and on a lunar base, as well as provide continuous measures of major processes and energy flows.

The Crew Crowds Into the Command Module as They Simulate Their Apollo 16 Mission

The simulator shows how cramped the Apollo 16 crew must have been in their command module. Command module pilot Thomas K. Mattingly, II, faces the camera. John W. Young, mission commander, faces away. The helmet of lunar module pilot Charles M. Duke, Jr., can just be seen behind Mattingly's. Such tight constraints could only be endured on a relatively short mission. The Space Shuttle has provided a "shirt-sleeve" environment for astronauts to work in. For longer stays on Space Station Freedom, *at a lunar base, or on a mission to Mars, even more attention will have to be paid to the comfort of spacefarers.*





Lunar Base Architecture

One concept for a habitat at a Moon base is this inflatable structure, protected from radiation by a continuous coiled bag containing lunar soil. Its construction crew lived in the simpler structure to the right, to which are attached a thermal radiator and solar power panels. The habitat, 16 meters in diameter, is designed to house 12 astronauts. It includes a gymnasium, which both makes use of the Moon's low gravity and counters its effects on the astronaut's physical condition; a control room; laboratories; a hydroponic garden, to provide fresh vegetables and to recycle exhaled carbon dioxide into inhalable oxygen; a wardroom for meals and meetings; and private compartments, located below the surface for extra radiation protection.

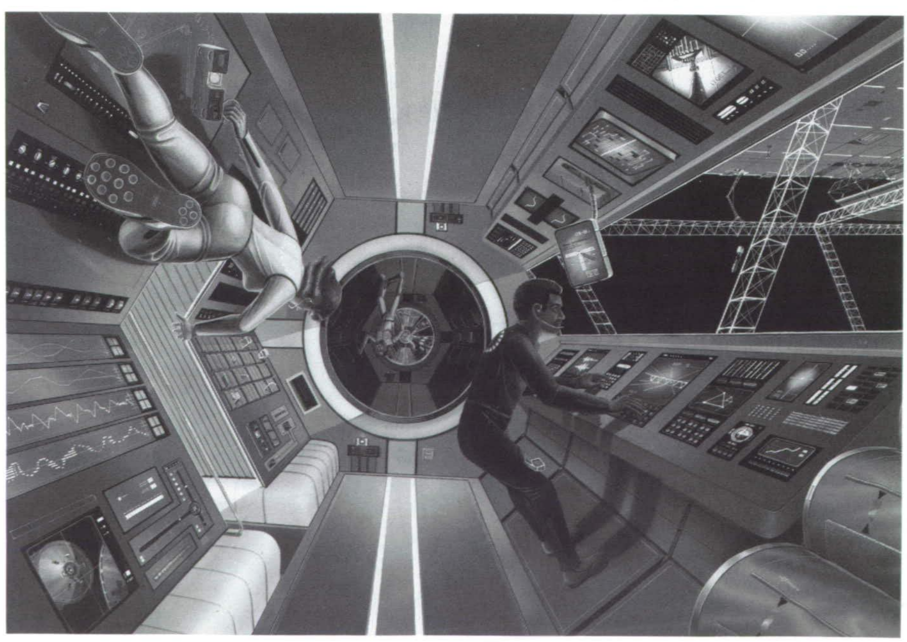
This painting shows a glove cabinet for handling lunar samples in a nitrogen atmosphere, as the Apollo samples have been handled on Earth for the past 20 years. With a permanent base on the Moon, such a substitute for the lunar environment would not be necessary. A more desirable procedure would be to take a small piece of a rock into the habitat atmosphere to study, throwing it away afterward, leaving the rest of the rock in place.

A problem not dealt with on the short Apollo missions but critical to a permanently inhabited lunar base is that of contamination by lunar dust. When the surveyors in the foreground return to the habitat, they will first pass through electrostatic wickets (seen on the left), which cause most of the dust to fall through the grate of this porch; they then remove their white coveralls, which protect the precision joints of the space suits from the gritty dust, and take an air shower in the dust lock; and finally they pass into the airlock to remove their suits.

These details show how a new environment requires innovative thinking.

The next 25 years offer lead time to plan for the more mature space communities to come. To cope with the unique conditions of life aloft, such as weightlessness and perpetual reliance on machinery, humans will adapt and acculturate, thus altering behavior. New living themes and patterns will change our sense of self, communication, dress, food, time, relationships, values, beliefs, mental processes, and work habits. To prepare for such revolutionary changes in the human condition, we need immediate research by cultural anthropologists and cross-cultural psychologists on such relocation issues as

- Crew selection and management for the space station and a lunar base. Increasingly heterogeneous and multicultural in composition, these crews will begin to stay in space for 180 days or more. Matters of personnel rotation, interpersonal and group dynamics, leadership and team building, in addition to the use of local space resources, demand more study now if such people are to work together efficiently, safely, and congenially.



An Early Concept of Life Onboard a Space Station in Low Earth Orbit

The selection and management of the increasingly heterogeneous crews who will live together under the stressful conditions of a space station or a planetary base are matters that demand more study now to ensure that such people will work together safely, efficiently, and congenially.

Artist: Jerry Elmore

NASA in the 21st Century: A Vision of Greatness

Kathleen J. Murphy

Abstract

We in the United States face an awesome challenge: NASA's role well into the next millennium must be decided *now*. The project goals to be achieved over the next quarter century need to be set in order *now*. Our scarce financial resources need to be allocated *now* to those projects that will maximize our long-term productivity.

NASA's course must be worthy, its execution impeccable, and its understanding of (and tolerance for) risk tailored to the unique developmental requirements of each situation.

- **Defining a worthy vision for the NASA organization**

  The first section of this paper discusses notions of greatness that have guided NASA in the past, presents values that might be delivered by NASA in the future, and examines the skills required for NASA to execute a vision of greatness.

- **Scoping a strategically significant mission agenda**

  The second section reviews three possible patterns of space development by NASA: (1) a mission to protect the ecology of the Earth, (2) the engineering of the technologies critical to space transportation and a healthy, productive life in space, and (3) the management of a major nonterrestrial resource project.

- **Sourcing—and sustaining—optimum financing**

  The paper's third section discusses potential sources of funds, opportunities for sustainable collaboration, and the life cycle of NASA's funding responsibility for its space development program.

Alternatives are abundant. The key to success, however, is our willingness as a nation to commit to a shared notion of greatness. Only steeled by such a commitment can we hope to make the wealth-creating technological advances and significant scientific discoveries to sustain our leadership into the 21st century.

A lot has happened since the 1984 NASA summer study, and even since the 1989 declaration by President Bush—on the occasion of the 20th anniversary of the landing on the Moon—that the U.S. space program will be redirected toward sustained exploration of space. Who would have imagined that in this short time peace would break out all over: that urgent longings for democracy would thrust China into a massive internal rebellion; that the yearnings of Eastern Europeans would thrash the Berlin Wall to dust; that in the space of a few weeks skeptical Romanian and Czechoslovakian

[redacted]

- Space personnel deployment systems that would provide a comprehensive acculturation program for life in space. Such a system might entail (a) recruitment and assessment, (b) orientation and training before departure, (c) onsite support and monitoring, and (d) reintegration upon return to Earth.

Conclusions

The increased number and diversity of people going into space beginning in the next 25 years requires research and development into more areas than just transportation, energy, and materials. It necessitates expansion of studies in the human sciences on issues of life support, safety, ergonomics, habitats, communities, and relocation of people, as well as the ecology of space resources. The situation would seem to warrant a more comprehensive, systematic approach to such planning.

The human race is in transition from an Earth-based to a space-based culture. Although this "passover" may take centuries, we are now taking the first revolutionary steps toward the time when we can regularly, economically, and safely extend out from low Earth orbit to the orbit of the Moon. Perhaps there we humans will really mature and achieve potential as we move out into the universe and a new state of being.

people would shake off their totalitarian systems in completely decent and peaceful ways. The surprising occurrence of these monumental events fills one with awe and wonder at the changes that lie ahead as we near the end of a millennium. One can only imagine the truths we have yet to discover, the many realities yet to unfold.

Full of hopes, dreams, visions of where these blossomings may lead us as a global community, we are at the same time crushed by alarming realities at home—weighed down by our massive budget deficit, surprised at the growing political irrelevance and eroding commercial competitiveness of the United States in the world, and shattered and saddened by the problems plaguing the former hallmark of our technological prowess, the National Aeronautics and Space Administration, in the aftershock from the Space Shuttle *Challenger* disaster—the January 1986 explosion that thrust the organization into a massive reevaluation. And now an agenda is under consideration that is so broad, so costly, and so far beyond the scope of human experience to date that the risks are extraordinary. It is only with courage and humility that cost estimates of these yet uncharted courses can even be attempted, as the potential for unpredicted events is enormous.

In November 1989, NASA laid out five approaches to going to the Moon and Mars using techniques and technologies the agency had studied for years and sometimes decades. Implementation would take more than a quarter of a century at a cost of $400 billion. That is regarded by the current Administration as simply too long and too much (Hilts 1990b). Eager to arrive at a realizable agenda, the Bush Administration has commissioned exhaustive brainstorming to refocus and redirect the U.S. space program, under the guidance of the National Space Council and its head, Vice President Dan Quayle. How can the "Bush vision" be molded into a challenging, yet realizable, program supported by adequate, consistent funding? How can NASA best prepare itself to bring the Bush Administration's redirection to fruition? This paper assesses NASA from organizational, strategic, and financial perspectives to determine if it is well positioned to meet the challenges of space exploration and development on into the next millennium:

- Defining a worthy vision for the NASA organization
- Scoping a strategically significant mission agenda
- Sourcing—and sustaining—optimum financing

Section 1: Defining a Worthy Vision

Leaders, through their visionary grasp of the possible, energize their followers and marshal them toward fulfillment of the goal. A vision is an energizing view of the future role or function of an organization, including its distinctive values, skills, and operating style. As a coherent directive, a vision statement provides focus: it provides a context for evaluating the appropriateness of potential missions and objectives; it suggests criteria for distinctive performance; and it empowers decision-makers throughout the organization to raise issues, assess options, and make choices. Always articulating the value to be delivered to those having a stake in an organization, the vision statement further provides a standard against which to evaluate external competitive positioning of the organization over the long term.

The Bush Administration perceives that there is a crisis of vision. Vice President Dan Quayle has commented that "Despite our continued scientific and technological preeminence, our Government has not done as well as it could have in marshaling the resources and the leadership necessary to keep us ahead in space. Our competitive advantage in technology has disappeared" (Hilts 1990b). Such a perceived crisis of direction cannot be tolerated for long, because NASA, our spearhead of technological innovation, has a responsibility of critical strategic significance to our nation. To ensure that NASA is on a worthy course, a vision of NASA's future greatness must be clearly defined, the value to be delivered by NASA must be fully understood, and the skills and style required to execute the vision must be specifically identified.

Notions of Greatness

The directive to explore and develop space is a boundless undertaking that is not likely to reach fruition in our lifetime (unless, of course, our technological breakthroughs advance at an exponential rate, or unless we have the good fortune to come to know other intelligence in the universe that has already figured everything out).

In contrast, the U.S. space program appears to have undergone short-term eras of leadership, demarcated by changes in President. The U.S. space program, framed by the President's vision perhaps more than any other program because of its discretionary financing, is often planned in terms of accomplishments realizable during that President's term in office. The implemented program is the result of an iterative process: The vision set by the President is constrained by the financial resources allocated by Congress, delimited by the technological capabilities held in hand by NASA (and other U.S. academic, commercial, and engineering institutions), and dependent on the willingness of the American people to sustain support over the project lifetime. There is an expense involved in this iterative process: Each change of vision creates new issues, alters priorities, and redefines standards. It is far more cost-effective to develop a strategy for human exploration of the solar system that can endure for at least 20 years, longer than the term of any one President, most members of Congress, or the average NASA manager (Aaron et al. 1989).

NASA has had at least three distinct directives since its inception in the 1960s, not counting the redirection under way since the Bush Administration took office (see table 1). A brief review of these "strategic eras" demonstrates the impact of Presidential vision on the organization up to now and suggests parameters for the most effective vision statement for the 1990s and beyond.

The Kennedy Vision: Establish U.S. technological supremacy in the world.

President John F. Kennedy launched the space program with a bold vision and a determined foresight that have not been enjoyed since. Envisioning the U.S. space program as the establisher of U.S. technological supremacy in the world, he chose as the focused mission objective a race to place a man on the Moon and return him safely to the Earth before the end of the decade. The entire program was a masterful demonstration of management efficiency and control, as the mission, relying on hundreds of thousands of subcontractors, was completed on time and on budget. The Apollo Program achieved the desired technology goals, as it reawakened interest in science and engineering, enhanced international competitiveness, preserved high-technology industrial skills, and marshaled major advances in computers and micro-miniaturization (Sawyer 1989). The program was awe-inspiring, enjoyed enormous funding support, and established a reputation for NASA that was to endure until it blew up with the Space Shuttle *Challenger* in January 1986.

TABLE 1. *The U.S. Manned Space Program, 1960-2000: Strategic Eras and Program Effectiveness*

Characteristics	1960s Kennedy Initiative	1970s Nixon Compromise	1980s Reagan Commercialization	1990s Bush Redirection
Vision	Establish U.S. technological supremacy	Provide economical access to space for military & commercial purposes	Foster a private-sector space industry	Establish U.S. as preeminent spacefaring nation
Mission	Place a man on the Moon & return him safely to the Earth	Create a reusable transport vehicle: capture 75% of commercial payloads worldwide	Build a space station to develop commercial products	Establish a permanent entity in space; begin sustained manned exploration of solar system
Budget	$ billion/yr 3.25 (26/8)	$ billion/yr 3.0 as of '74	$ billion/yr 7.5	$ billion/yr 13 est. (400/30)
Performance	On time, on budget (one-time event)	Late, over budget (missed economic objective)	Late, over budget, redefined several times, uncertain	Taking a fresh new look
NASA management	Masterful	Ineffective	Confused	Potential resurgence
NASA bargaining leverage	Strong: generous support & funding	Moderate: constant renegotiation to increase funding	Weak: constant budget-cutting & rescoping	Potential improvement
Public esteem	High, inspired	Neutral	Seriously eroded	Potential renaissance

Sources: Banks 1988, Chandler 1989, Chandler and Mashek 1989, Sawyer 1989, Steacy 1989.

Apollo 14 Rollout, Nov. 9, 1970

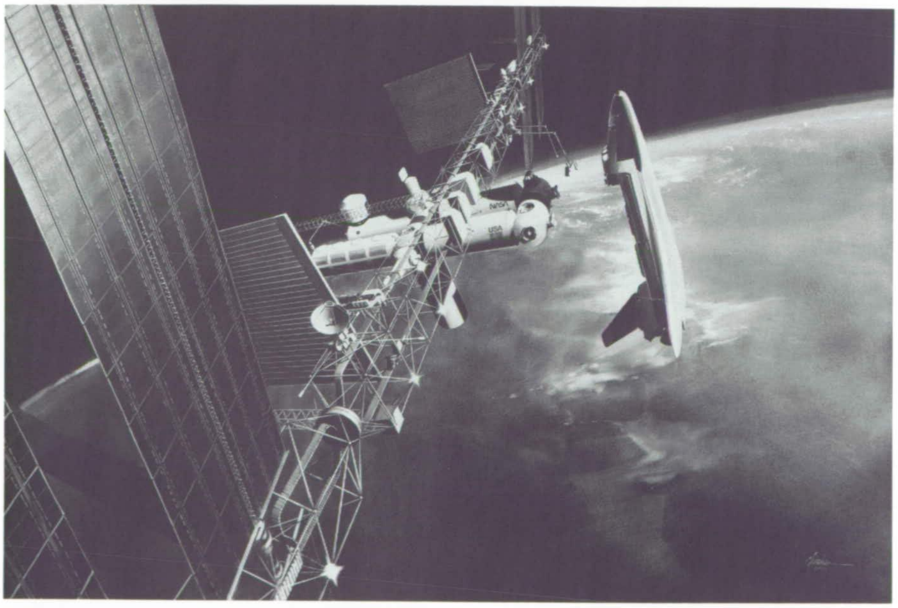
The Nixon Vision: Provide economical access to space for military and commercial purposes.

President Richard M. Nixon chose a very specific vision which, if successful, would have provided important commercial benefits to the United States and, if realized during his term of office, would have been a credit to his administration. He envisioned NASA as providing economical access to space for military as well as commercial purposes. The mission, which was specifically articulated, was to create a reusable transport vehicle that could capture 75 percent of the commercial payloads worldwide. While a reusable Space Shuttle has been developed and put into operation, it has never achieved the economic objectives which were an essential component of the vision. The Shuttle will simply never be able to provide the cheap, versatile, and reliable access to space it was supposed to, because it is a complex and sophisticated vehicle—a Ferrari, not a truck (Budiansky 1987-88). Nevertheless, the National Academy of Sciences has noted that the Space Shuttle engine was the only significant development in space propulsion technology in the past 20 years.

Lift-Off of STS-1, April 12, 1981

The Reagan Vision: Foster a private-sector space industry.

The directive to establish a permanently manned space station was a subsidiary mission in the Reagan era, subordinate to his vision of a Strategic Defense Initiative (SDI). However, to be worth $30 billion, the space station should really serve some worthwhile national purpose. Commercial applications have obviously been grossly overstated, As companies have backed off space manufacturing since solutions have already been developed on Earth. Furthermore, such a mission had been rejected in favor of the lunar mission by President Kennedy in 1961, a space station not being considered bold enough for the 1960s (Del Guidice 1989) (although Skylab was built, flown, and manned three times in the 1970s).

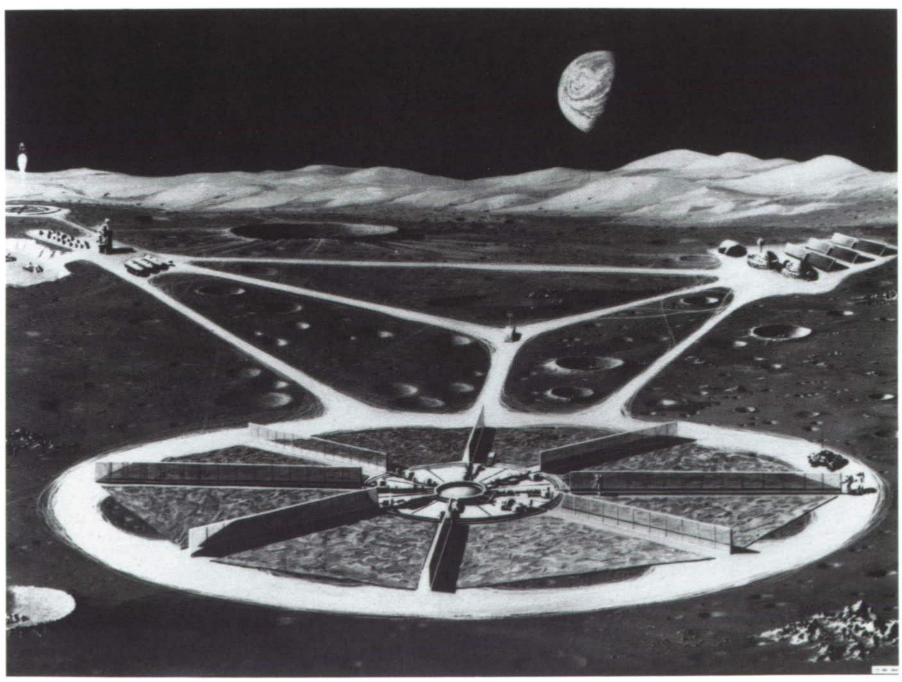


***Concept of Space Station* Freedom**

Artist: Al Chinchar

The Bush Vision: Establish the United States as the preeminent spacefaring nation.

President George H. W. Bush's tentative vision for the U.S. space program is of "spacefarer," suggesting a navigator, one who sets or charts a course. His priority missions are to establish a permanent entity in space and begin sustained manned exploration of the solar system. At this writing, the mission agenda of the Bush Administration has not been finalized. Vice President Quayle has requested that the NASA Administrator, Richard H. Truly, ensure that our space exploration program is benefiting from a broad range of ideas about different architectures, new system concepts, and promising technologies, as well as opportunities to cut costs through expanding international cooperation. He asked Truly to query the best and most innovative minds in the country—in universities, at Federal research centers, within our aerospace industry, and elsewhere. NASA will take the lead in the search and will be responsible for evaluating ideas (Broad 1990a).



Concept of a Lunar Base, Featuring the Radiator of Its Nuclear Power Plant

Alternate: The Havel Vision: Uncover the secrets of the universe.

In a 1990 interview,* Vaclav Havel, President of the Czechoslovak Socialist Republic, stated that we still have a long way to go in our development, as we still have not yet "uncovered the secrets of the universe." It is interesting to select such an idea as an alternate vision, as a "control" to assess whether President Bush's notion of greatness goes far enough and is sustainable over the long term. Effectively, the difference between "spacefaring" and "secret uncovering" is that between the means and the end, the journey and the arrival.

Vaclav Havel, a former political prisoner and a playwright, has demonstrated a clarity and a profundity in his political statements at Czechoslovakia's helm that are truly visionary and thought-provoking. On the occasion of his visit to the U.S. Congress in February 1990, he articulated the pace of change: "The human face of the world is changing so rapidly that none of the familiar political speedometers are adequate. We playwrights, who have to cram a whole human life or an entire historical era into a two-hour play, can scarcely understand this rapidity ourselves." And he articulated his vision of the role of intellectuals in shaping the new Europe—which can be compared to the role of space technology and science in clearing the path for the space age: "The salvation of this human world lies nowhere else than in the human heart, in the human power to reflect, in human meekness, and in human responsibility. The only genuine backbone of our actions—if they are to be moral—is responsibility. Responsibility to something higher than my family, my country, my firm, my success" (quoted by Friedman 1990).

Recognizing that everything we know of any importance about the universe we've found out in the last 50 years or so (Wilford 1990a), it would not be unrealistic to expect great truths to be unfolded in the 50 years to come. Numerous projects on NASA's drawing boards today promise to unlock important secrets in the near future. For example, it is hard to imagine a more exciting secret than whether or not there is other intelligent life in the universe. The Search for Extraterrestrial Intelligence (SETI), a proposed $100 million, 10-year project, funded by NASA but operated by an independent nonprofit group, plans to build a highly advanced radio receiver that will simultaneously scan 14 million channels of radio waves from

*With Barbara Walters on the ABC television program *20/20.*

existing radio telescopes around the world. The National Academy of Sciences has stated that it is hard to imagine a discovery that would have greater impact on human perceptions than the detection of extraterrestrial intelligence (Broad 1990b).

Expected Values

The vision statement conveys standards of excellence: "Be a technology leader." "Provide transportation economically." "Be an explorer, a navigator, a spacefarer." It determines which values are given precedence, thus providing a standard by which to determine relative degrees of excellence, usefulness, or worth of tasks performed within the organization. Each value to be delivered targets a potential competitive advantage or some economic leverage to be derived from realization of the vision. The purpose of a commercial organization is to create wealth for its shareholders. As a Government-sponsored institution, NASA has a value to its shareholders—the U.S. taxpayers—that is much broader and more complex.

A review of the literature reveals a broad range of opinions held by the public regarding what NASA's value is. Probably the lively debate over the efficacy of the space program exists precisely because of this wide disagreement. The composite list of "values" that NASA "should" be delivering, which follows, seems remarkably similar to Maslow's hierarchy of needs (fig. 3), from the most basic physiological need for survival (deriving economic "bread" from commercial activities), through safety, social, and esteem needs, and finally to the peak experience of creativity and self-actualization. Maslow's theory postulates that the most basic needs must be satisfied before higher needs can be addressed.

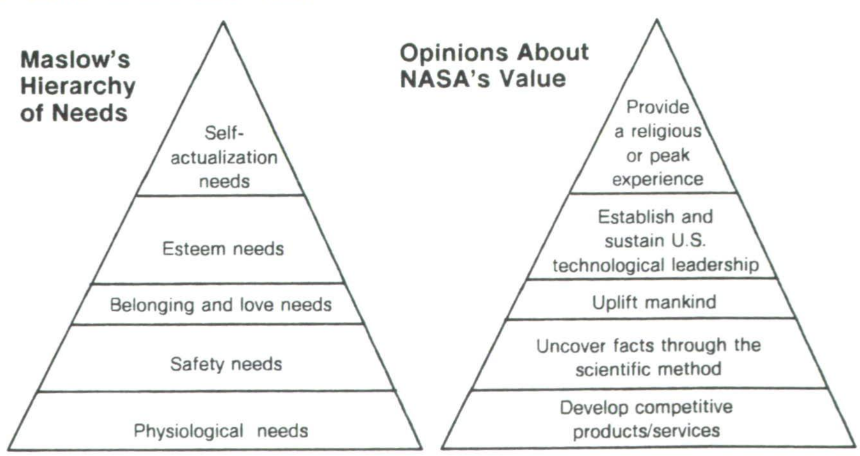


Figure 3

Maslow's Hierarchy of Needs and Opinions About NASA's Value

A leader of the humanistic psychology movement, Abraham Maslow was concerned primarily with the fullest development of human potential; thus, his burning interest was the study of superior people. His theory of human personality has become probably the most influential conceptual basis for employee motivation to be found in modern industry. The needs occur in the order in which they are presented, physiological first. Until one level of need is fairly well satisfied, the next higher need does not even emerge. Once a particular set of needs is fulfilled, it no longer motivates.

Source: Rush 1976.

Develop products and services with clear economic advantages.

Many look to NASA as a wellspring of new product and service innovations that are expected to keep the U.S. economy competitive in the world. This economic focus expects a perfectly managed program (on the order of the Apollo days) with only outstanding economic results. Any news about the difficulties of engineering the highly complex technologies of today is not welcome. NASA is given causal responsibility for ensuring U.S. competitiveness in the world: "Space leadership and technological leadership are tied together. Just as technological leadership and American competitiveness are tied together" (Anderson 1988). Furthermore, NASA is expected to fuel as well as fully interact with the private sector in their joint development and spinoff efforts. "In the vastness of technology, mutual dependence between government and the private sector nourishes both"—Thomas G. Pownall, Chairman, Martin Marietta (Rappleye 1986).

Uncover facts through the scientific method.

Others see NASA as a herald of science: both putting scientific knowledge to work in the engineering feats of space exploration and adding to our scientific understanding of the solar system. This view suggests an approach to space exploration that minimizes threats of loss of life or health, a highly disciplined approach grounded in the scientific method. Indeed, with the exception of the race to put the first man on the Moon, NASA has approached solar system exploration in a step-by-step fashion. And remarkable engineering and scientific accomplishments have been made by NASA's missions to the Moon (Ranger, Surveyor, Apollo) and to the planets (Mariner, Pioneer, Viking, Voyager). Scientist astronaut Sally Ride thinks NASA should continue in this tradition. She has stated that NASA should avoid a spectacular "race to Mars" and establish a lunar outpost as part of a measured exploration of the solar system. "We should adopt a strategy to continue an orderly expansion outward from the Earth . . . a strategy of evolution and natural progression" (quoted by Broad 1989). Other space experts would like NASA's scientific focus to be inward toward the Earth. "We'd better pursue the things that work in space, like surveying the Earth's resources, weather patterns, climatic change—things of direct and daily human importance" (Brown 1989).

Uplift mankind.

There are more emotionally motivated constituents who value NASA not for what it does scientifically but for the social, cultural, or political impact it has on our collective consciousness, whether national or global. The success of the space program as "a cultural evolution may open many new options, including opportunities to ease global tensions, help the developing world, and create a new culture off our planet" (Lawler 1985). "The U.S. will again lead the world in developing space for the benefit of its citizens and future generations throughout the world" (Rockwell 1986). "Going to Mars is an international endeavor. Political benefits can be derived immediately—not 30 years from now but every year, through a joint project with other countries, and the Soviet Union in particular" (Del Guidice 1989). Perhaps the most shining example of this ability of the space program to uplift and unite is the phenomenon of more than 600 million people who gathered at their local television sets around the world in July 1969 to witness the U.S. landing on the Moon 241 500 miles away.

Establish and sustain U.S. technological leadership.

Others view NASA as the determinant of our technological leadership in the world and therefore a source of esteem. "It is humanity's destiny to strive, to seek, to find . . . it is America's destiny to lead" (Rosenthal 1989). Essentially, "we must either reaffirm U.S. preeminence in space or permit other nations to catch up or surpass us at the crucial juncture" (Gorton 1986). Under this value system, leadership can be dangerously misconstrued to mean "pay for everything." True opportunities for differentiated, competitive leadership need to be understood and aggressively pursued; however, the basis of world esteem for our space program should be authentic technological achievement and not simply financial daring.

Provide a religious or peak experience.

Finally, there is a profoundly fulfilling dimension to truly marvelous achievements and truly humbling failures. "There is something almost religious about man in space. The human exploration of the solar system appears quasi-religious, while automated exploration is 'pure science'" (Brown 1989).

Space exploration has a profound moral dimension that cannot be transgressed. The natural law, when followed, leads on to fulfillment of the mission but, when violated, leads to difficulties and even death. In these days of avarice and deception that seem to escape the heavy hand of justice, the joys and sorrows of space exploration are tied to a morality that does not play favorites. Compare the infamous Wall Street "junk bond" crisis or the savings and loan debacle, engineered by those who made their own rules and used the system for personal gain, violating all standards of fair play, to space explorers, who are obliged to uncover "the" rule and advance strictly within its limits. In spite of the wonderful heroism of the seven astronauts who rode the *Challenger* to its demise, the violation of the temperature limits of the "O" rings led to immediate ruin. It is the very discovery of the rule—how things work—that makes the quantum leap possible. Effective communication of this "truth" and "honor" of technological and scientific exploration is sure to shift prestige away from Wall Street and draw career candidates into engineering and science.

Space exploration will entail extraordinary adventure and discovery, but also enormous risk and personal sacrifice. The deep personal commitment that will be required to depart on the long journey replicates the religious motif of death and resurrection:

> I shall stretch out my hand unhesitatingly towards the fiery bread. . . . To take it is . . . to surrender myself to forces which will tear me away painfully from myself in order to drive me into danger, into laborious undertakings, into a constant renewal of ideas, into an austere detachment. (de Chardin 1972, p. 23)

One might wonder how a Government-sponsored research agency could possibly fulfill this broad range of expectations. In fact, excellent performance of the task which NASA does best—advancing technology and science—will provide both practical and ennobling results.

> . . . if some observer were to come to us from one of the stars what would he chiefly notice?
>
> Without question, two major phenomena:
>
> the first, that in the course of half a century, technology has advanced with incredible rapidity, an advance not just of scattered, localized technical developments but of a real *geotechnology* which spreads out the close-woven network of its interdependent enterprises over the totality of the earth; the second, that in the same period, at the same pace and on the same scale of planetary cooperation and achievement *science* has transformed in every direction—from the infinitesimal to the immense and to the immensely complex—our common vision of the world and our common power of action. (de Chardin 1972, p. 119)

It is the almost instantaneous globalization of technological innovations and the transformative impact on quality of life of scientific breakthroughs that contributes, day by day, to the emergence of a vision of one citizenry, one planet.

If this set of expected values is held up to the Bush and Havel visions, we see that the Bush vision may influence technology development and require the advancement of science to steer the course; the Bush journey may establish our leadership position—if we are the first to make it; the journey may require courage and thus be inspiring. But Bush's vision does not have the closure that Havel's vision has. If we make the journey in order to uncover the secrets of the universe and if we succeed in realizing that vision, it is certain that a peak experience filled with awe and wonder will be an integral part of "truth's" unfolding.

Elements of Excellent Execution

A worthy vision, excellently executed, reaps outstanding results. Skills form the bridge between strategy and execution. The expected values determine the kind of skills needed. American taxpayers look to their national space exploration and development program for highly competitive new products and services, scientific facts, an uplifting perspective, preeminent technological leadership, and ethical and moral fortitude.

Excellence, grace, skill in execution conveys an organization's essence or style. But NASA does many things. NASA is not a single business unit, but a broad, rich organization with activities under way on many levels. What does NASA do? NASA is a problem-solver, trying to diagnose the startling environmental symptoms occurring on Planet Earth; NASA is an innovative engineer of technological advances; NASA is a conceiver, designer, implementer of "big science" experiments and exploration projects; NASA is the developer of the Space Shuttle and Space Station *Freedom* and would like to be the developer of colonies on the Moon and Mars; and NASA is the operator of the Space Shuttle, although operations are clearly not within its charter. Each set of functional tasks requires a different set of skills and styles of management as well as distinctive guidelines and criteria for measuring results and assessing whether they are appropriately aligned with the overall vision. It is the vision, however, that pulls all of these incongruous tasks together and weaves their diverse contributions into a single recognizable achievement.

However, the vision must be decided upon: Which vision, "spacefarer" or "secret uncoverer," best focuses the NASA organization on worthy accomplishments over the next 20 to 30 years? My purpose here is not to promote one visionary concept over another but rather to demonstrate the role and function of a vision in coloring the entire decision-making process within an organization.

The Skilled Professional

Excellent performance of NASA's multitude of tasks requires a rich array of the very best skills available in America today. Nothing less than the very best minds should be brought to bear on this major potential to revitalize our nation. The critical skills essential to executing NASA's numerous tasks include

- Visionary leadership
- Technical competence
- Entrepreneurial judgment
- Problem-solving ability
- Project management expertise
- The ability to innovate/ experiment/create
- Navigational skills

The notion of vision ranks these critical skills and determines who will implement the vision. If we want to be the preeminent spacefarers, then perhaps navigational skills and entrepreneurial judgment will be the critical skills required by the organization. However, if the pursuit is of truths about the universe, then perhaps the ability to solve problems and the ability to innovate, experiment, create will be the most critical skills required.

The skilled professional may be homegrown or hired with the appropriate experience or contracted to fill a short-term need. But we will apply different evaluation criteria in searching for a "spacefarer" than in searching for a "secret uncoverer." To realize the "spacefarer" vision, we would look for the characteristics of an explorer, an adventurer, a risk-taker. To accomplish the "secret uncoverer" vision, we would need a more rigorous expertise based on proven results in innovating, discovering, inventing. The first suggests a fortitude in facing the unknown. The second suggests facing the unknown, wrestling the unknown to the ground, and rising victorious with insight into its parts and how the parts relate to each other to create the whole. The criteria for selection become more rigorous; the measures of successful performance, more precise.

The only way to reduce the timeframe and cost of research and experimentation and maximize effectiveness is to bring the best minds to bear on critical problems. Even if a premium must be paid over industry rates to attract such talent, the resulting maximization of NASA's output with respect to its vision would more than compensate for the increased investment in human capital.

To be able to respond agilely to problems and projects as they arise, NASA should be exempt from certain Civil Service regulations and be given flexibility in personnel hiring, advancement, retirement, and the assembling and disbanding of teams, as well as the resources to reward truly significant, ground-breaking, wealth-creating contributions.

The Pivotal Job

The pivotal jobs are those that are critical to demonstrating the vision. Those holding such jobs are effectively the delegated vision actualizers who, given sufficient leeway, exercise their judgment, intuition, and responsibility in service of the vision.

Jobs are considered pivotal if they are essential to convincing the American taxpayer that NASA is producing the desired result or achieving the desired strategic objective. They demonstrate that the vision is becoming actualized. Pivotal jobs might include

- The visionary leader, who can see, smell, taste, feel the fruition of the project
- The engineer, who ushers in technological breakthroughs
- The entrepreneur, who spins them off
- The scientist, who methodically unfolds discoveries
- The project manager, who shepherds the contributions of thousands of specialists within the "real-world" parameters of schedule and budget
- The communicator or brainstormer, who constantly stirs up, tears apart, refreshes, revitalizes the organization
- The astronaut, who navigates the spacecraft, who braves the unknown, and who will explore, develop, and inhabit space beyond our Planet Earth

If we are to be a nation of spacefarers, it is the astronaut who holds the pivotal job of demonstrating to the American people that we are indeed venturing out into space, navigating beyond Planet Earth. However, if we are to uncover the secrets of the universe, the engineer, the scientist, the brainstormer or communicator might hold the pivotal job, as such tasks embody the exhaustive search for unnoticed relationships and their significance.

The Focused Team

The projects on NASA's drawing board are beyond the ability of any single organization to implement, let alone single individuals. So, although it is critical that each individual represent the very best human potential our country has to offer, each must also have the uncanny ability to enrich, nourish, and apply that expertise in pursuit of a common goal, through highly focused teamwork. The end-product parameters must be clearly defined, and the accumulating insight must be continously shared among team members.

An individual professional's skill permits ready execution of a task at a high level of competence. An issue of concern is the potential dichotomy between the highly specialized professional and the highly synergistic team. Each specialist has his own vision of quality achievement and his own sphere of personal interests. Only through an over-articulated, single noble vision can sufficient energy be unleashed to inspire all toward a common goal. Such approaches as establishing broad spheres of responsibility, using teams extensively, and searching for job rotation opportunities continuously can nourish an ability to see connections and implications and foster more efficient, decentralized decision-making.

As an example, Ingersoll-Rand collapsed the design cycle of a new handtool to 1 year—one-third the normal development time—by breaking down the barriers within the entrepreneurial team and allowing sales, marketing, engineering, and manufacturing to work in unison; i.e., getting everyone to "play in the same sandbox." To avoid the "not-invented-here" syndrome, a core team representing all functional areas held weekly meetings to ensure that, among other things, all members had a stake in every step and it was a team project (Kleinfield 1990).

Staying centered on the creative process and remaining always fresh and innovative requires the ability to focus. The Bureau d'Economie Theorique et Appliquee (BETA) research group believes that innovation is, above all, a process. BETA has conducted four large research programs in the past 10 years, including a study of the space program to illustrate technological learning or change within an industrial network. They have concluded that innovation is an evolutionary phenomenon rather than a sudden happening (Zuscovitch, Heraud, and Cohendet 1988).

A compromising environment may get the journey under way, but it will not lead to the fullness of "truth." Such pressures as scoring achievements within a term-in-office timeframe; restricting a project to certain cost limits dictated by the national debt; establishing premature international collaboration simply because we are broke; sticking to known and established technologies no matter how inapplicable they may be; readily accepting unproven technologies because they're supposed to be cheaper—all these pressures constrain the investigative process and lead to half-baked results. If we are going to conduct an exploration program, we should provide the time and money to do the job right.

Where does one begin? How to achieve change, how to start the change process, how to assess whether members of the organization are prepared for change, how to handle obstacles to progress—these are all issues of concern, yet they are all surmountable. The important point to keep in mind is that organizations change all the time. Change readiness can be assessed at all levels of the organization, jobs can be redesigned, skills can be built, and any vision, eagerly embraced, can be brought to fruition.

The Coordination of Complexity

The most significant feature of the NASA space program, as compared to all the other programs on Earth today, is the enormous complexity of each individual project and the cumulative complexity of the program in its entirety. The simple experience of engaging our minds in the mastery of such mega-scale products, processes, and projects creates an expertise that serves us well in all aspects of our economic endeavors and in our global competitive positioning. In other words, this managerial experience—in itself—provides a unique competitive advantage to our nation.

The Brilliant Achievement

What makes an achievement stand out in our mind as brilliant is colored by our vision. The Apollo landing on the Moon is an example of an impeccable journey. The project was perfectly timed, sequenced, and costed out to run like clockwork. In contrast, the Hubble Space Telescope (fig. 4) has had a sporadic history—on again, off again—over a period of 40 years. It was championed by one person, Dr. Lyman Spitzer, from 1940 to 1950. Project Stratosphere, a prototype 12-inch telescope carried by balloon, was launched in the 1950s. NASA took over in the 1960s and successfully launched two precursor observation launches. Finally completed and launched in April 1990 at the cost of $1.5 billion, more than three times the original projected cost of $435 million, the Hubble telescope has been riddled with difficulties, including the discovery that one of the mirrors was apparently ground to the wrong curvature. Yet the vision remained the same throughout (Wilford 1990c).

Dr. Lyman Spitzer, now 75, wrote in his first proposal for a space telescope over 40 years ago that, "The chief contribution of such a radically new and more powerful instrument would be, not to supplement our present ideas of the universe we live in, but rather to uncover new phenomena not yet imagined, and perhaps to modify profoundly our basic concepts of space and time" (Wilford 1990c).

Under the vision of spacefaring, this project might be regarded as a disaster, because the spacefaring vision focuses on the quality of the journey. In fact, the journey was terrible. The project was subject to numerous postponements, overruns, and delays, and it still (1990) has serious problems even after launch. Yet when the first insightful photograph returns from the telescope, if one of the answers to the three key questions—How fast is the universe expanding? How old is the universe? What is the fate of the universe?—is disclosed, then, under the secret-uncovering vision, this project will have been a tremendous success.

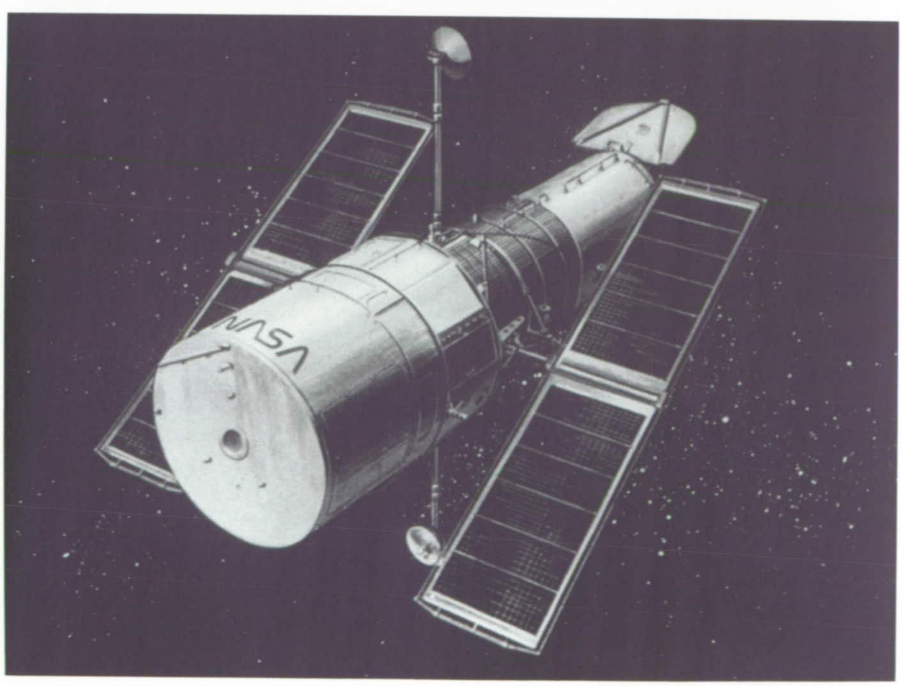


Figure 4

The Hubble Space Telescope

Section 2: Scoping a Strategically Significant Mission Agenda

The space program promises to provide a chance to restore Planet Earth to abundant health, a running start on technology leaps beyond our imagination, and access to boundless resources.

> The U.S. space program is not the only driver of U.S. technology . . . but [it] is a direct and major driver of those kinds of technologies that will drive the world market of the next century. (Anderson 1988)

> The Space Industry will be a leading indicator of all other industries in the future— Yukiko Minato, Ministry of International Trade and Industry, Japan. (Buell 1987)

> In the long term, a key to humanity's continued evolution will be the penetration of space and the economic and scientific exploitation of the solar system's inexhaustible resources and unique physical characteristics. (Glaser 1989)

The United States has been a trailblazer in space development. Since the heady days of Apollo, the United States has enjoyed a reputation for unprecedented large-scale project management expertise, long-lasting unmanned planetary exploration, a deep institutional experience base in NASA, and unparalleled aerospace leadership—all decisive competitive advantages that have benefited commercial, as well as public endeavors.

However, 20 to 30 years ago, space exploration and development programs were narrowly focused. The science and engineering problems faced today, such as alloys, fuels, distances, are much more complex than those wrestled with during the Apollo Program. A strategy needs to be formulated that effectively allocates finite resources among carefully selected objectives in a sequence that maximizes results. Important strategic insights can be derived from examining several potential mission scenarios for NASA.

Remarkably, a close examination of NASA demonstrates that the agency has been active in promoting and nurturing initiatives across the board—in every strategic space development segment. President Bush seems to want to continue a tradition of independent, full-scale initiatives. While the notion of international participation was not entirely absent from Bush's July 20, 1989, speech, it was heavily overshadowed by a nationalistic message: "What Americans dream Americans can do." We should pursue these goals "because it is America's destiny to lead." This phrasing suggests that America is going to pay the first 100 percent, and, if others want to add on top of that, they can (Chandler 1989). Such a posture needs careful evaluation.

This paper reviews three segmentations of the space development arena to demonstrate potential areas of strategic leverage for NASA, as the agency seeks to clarify its role and function within the global space development industry:

1. **Consumer-driven innovation**: The entrepreneurial traits of customer-driven innovation and incessant scrutiny of the marketplace are essential components of effective market-focused strategy development. The only real "consumers" of the space program are the citizens of Planet Earth. It is eminently wise to focus on their needs as buyers—their higher needs for a healthy planet for their children and their children's children. The ability to scrutinize profoundly the resource components of Planet Earth and to begin to understand the interaction of economic and natural variables promises to provide a contribution by NASA and other national space agencies around the world that is unprecedented.

2. **Capability-driven innovation**: There are specific gaps in our tools, products, and processes that prevent prompt exploitation of space. Nothing short of major technological leaps must be masterminded. The originators of such technological breakthroughs have typically seen them spin off into lucrative commercial ventures.

3. **Destination-driven innovation**: The prospect of setting up colonies on such forbidding planetary bodies as the Moon and Mars makes sense only when the colony is viewed as a base from which to exploit resources. To access the rich resources of our neighboring planets, to capitalize on manufacturing breakthroughs achieved only in low-gravity conditions, to test the possibility of transferring some of our heavily polluting industries off Planet Earth (taking care not to pollute our neighboring planets)—these tasks require a supporting infrastructure that includes the advancement of megaproject management expertise. The colonization of the Moon and Mars effectively requires the creation of entirely new industry and infrastructure sectors, which will invariably have a profound impact on our lifestyle and business approaches on Earth.

In 1988 the National Academy of Sciences recommended that the United States undertake a multibillion-dollar space science initiative that would redirect the U.S. space program in the early 21st century. They recommended that

1. An intense, continuous program be established to monitor Earth's climate, resources, and numerous other factors important to the planet's health.

2. A search for planets in distant solar systems be given a high priority.

3. A number of sample-return missions be sent to nearby space bodies.

4. Many new missions in space biology and medicine be undertaken.

The first recommendation supports the Mission to Planet Earth, the second and third support exploration efforts which are preliminary to selecting a destination, and the fourth recommendation encourages regenerative life support technology—a capability to be developed. These proposals, in the report "Space Science in the 21st Century—Imperatives for Decades 1995-2015," would require NASA's budget to grow significantly (Covault 1988).

Consumer-Driven Innovation: The Business of Protecting Planet Earth

The "Planet Earth" consumer is literally consuming the planet:

> Consider the situation we face on the eve of the 1990s: We are generating waste, both solid and hazardous, at a rate far exceeding our ability to dispose of it; global temperatures are inching upwards; our protective shield of ozone is disappearing at the same time as the earthbound, harmful ozone continues to exceed safe levels in many of our cities; acid rain is killing much of our aquatic flora and fauna and damaging many of our forests; and the world population has reached 5 billion and continues to climb rapidly. (Glass 1989)

More alarmingly, further growth is essential: A fivefold to tenfold increase in economic activity is required over the next 50 years to meet the needs and aspirations of the world population and reduce poverty. This will place a colossal new burden on the ecosphere (MacNeil 1989).

Space science has already proven that it can contribute substantially to our understanding of Earth's problems: the greenhouse effect on Venus and ozone depletion on

Mars provided insights that alerted us to potential dangers in our own atmosphere. Imagine how potent direct focus by the international space establishment on Planet Earth promises to be. The Apollo 8 photo of our planet afloat in space showed us that, as Buckminster Fuller put it, we are passengers on Spaceship Earth. The Earth is all we've got—at least for now.

All products brought to market on Planet Earth follow a similar activity flow from analyzing the market and customer need, through designing the product, purchasing or sourcing the raw materials, and manufacturing, to distributing and selling the product (see table 2). There are three critical roles that NASA could play in the United States, other national space agencies could play in their respective countries, and all these agencies could play jointly on Planet Earth to align business activities with ecology-preserving systems:

- Provide an information base for delimiting constructive and destructive use of resources on Planet Earth.

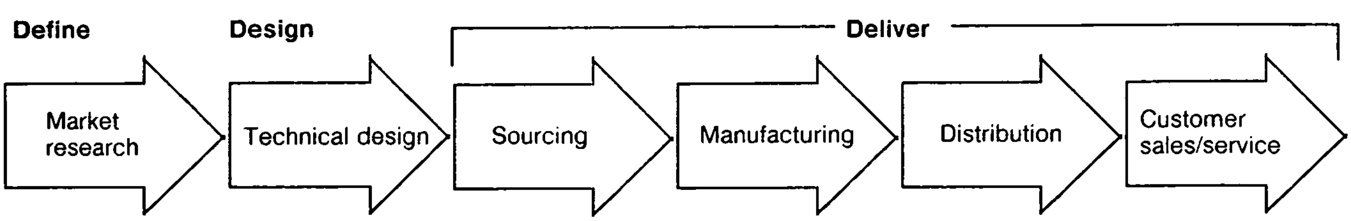
- Provide technology design initiatives that demonstrate regard for ecological limitations.

- Participate in policy formulation efforts intended to promote global industrial restructuring—including consideration of transferring the most polluting industrial activities to off-planet locations.

Market Research: Point the way to save the planet

Growth must be structured in ways that keep its enormous potential for environmental transformation within safe limits—limits which are yet to be determined. Clearly defining the parameters within which Planet Earth can be restored to health can provide powerful directives. For example, one author states that to stabilize concentrations of carbon dioxide at present levels, an immediate reduction in global manmade emissions—chiefly from the burning of such fossil fuels as coal and oil—by 60 to 80 percent would be necessary (Shabecoff 1990a).

TABLE 2. *The Business System for Bringing a Product to Market on Planet Earth*



NASA has a project under way which may identify just such degrees of tolerance: The Mission to Planet Earth is a "global habitability mission" (Brown 1989) involving a very substantial purely scientific component directed toward real human problems. It is intended to point the way to save the planet. Also referred to as Earth Observing System (EOS), it is an international initiative consisting of five giant orbiting platforms [two from NASA, two from the European Space Agency (ESA), and one from the National Space Development Agency (NASDA) of Japan], each carrying the largest and most sophisticated array of remote-sensing instruments ever assembled. The mission will begin a 15-year period of observation in the mid-1990s. This will become one of the largest space science projects ever, costing the United States $1 billion per year (Cook 1989).

The list of critical processes that impact Planet Earth's ecological system and must be monitored is extensive, including changes in concentrations of greenhouse gases and their impact on temperature; the effect of ocean circulation on the timing and distribution of climatic changes; the role of vegetation in regulating the flux of water between land and atmosphere; global circulation and processing of major chemical elements such as carbon, oxygen, nitrogen, phosphorus, and sulfur—principal components of life—as well as carbon dioxide, methane, and nitrous oxide (More than 70 000 chemicals synthesized by humans affect the global environment.); and processes of evaporation and precipitation, runoff and circulation (Clark 1989).

The end product of this international undertaking will be an information base for decision-making—the findings of scientific research and planetary monitoring. It is hoped that the environmental impact of business decisions will be demonstrated in a fact-based manner. The real environmental costs of human activities have not been isolated to date; thus, calculations of business efficiencies have been skewed in favor of the convenient. The dilemma involved in choosing process technologies, governed as they are now by private, generally short-term, profit-maximizing responses to market forces rather than long-term concerns about environmental quality, could more effectively be resolved with the data base that Mission to Planet Earth promises to assemble.

President Bush has expressed his willingness to prevent compromise while appreciating the need to redefine business standards in the marketplace: "To those who suggest we're only trying to balance economic growth and environmental protection, I say they miss the point. We are calling for an entirely new way of thinking, to achieve both while compromising neither, by applying the power of the marketplace in the service of the environment" (Shabecoff 1990b).

Technical Design: Define environmentally safe products and processes

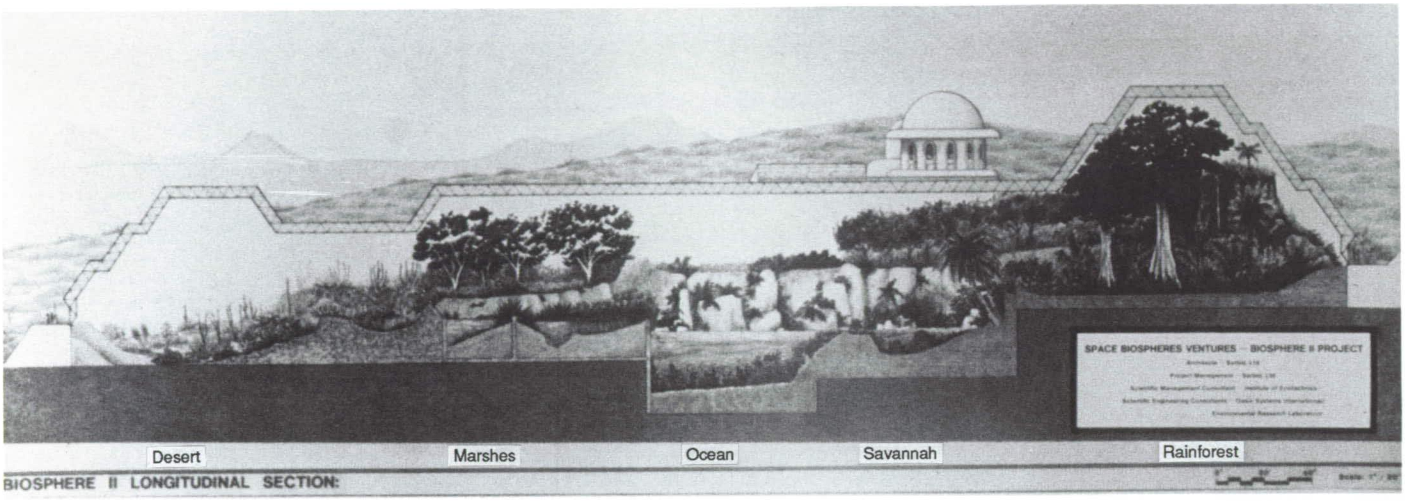
Technologies that can be utilized on the scale necessary to support sustainable economic development must be resource-conserving, pollution-preventing, and environment-restoring, and themselves economically supportable. Sheer invention is the only effective way out of our major ecological problems, as the very technological foundations of our economy need to be totally revised. What we need is an economy that will not consume scarce resources and will not generate pollution.

Begin with the environmental constraints and then design the product: NASA is initiating a process that it believes may serve as a model for government, industry, and environmental groups. Its cornerstone is getting together before a technology is developed to determine what technological advances must be made to render a product or process environmentally and economically acceptable. Looking at the environmental issues ahead of hardware issues, they have even gone one step further: they have resolved not to develop the product or process if the environment is compromised (Leary 1990). In the case in point—development of a high-speed passenger plane—walking away would be enormously difficult, as competition stands in the wings: Aerospatiale, the French aircraft company, is studying the next-generation supersonic transport to replace the Concorde; the Japanese government has begun serious research; and the Soviet Union has begun studies on a transport plane that could fly at 5 times the speed of sound (Leary 1990).

Preliminary studies commissioned by NASA indicate that building such an aircraft is possible. However, current aircraft technology, including the best materials and engines, could not produce an acceptable aircraft, according to Boeing. The Lawrence Livermore National Laboratory concurs, having calculated that a fleet of 500 supersonic airliners using existing engine technology would seriously deplete the ozone layer by 15 to 20 percent, almost 3 times the damage from chlorofluorocarbons. NASA plans to spend $284 million over the next 5 years to find out whether the required technological advances to develop an environmentally safe high-speed plane can be achieved. The program will center initially on airport noise, sonic booms, and engine emissions that could reduce the atmosphere's protective ozone layer (Leary 1990).

Experiment with new processes that will protect the environment:

- Ecologically safe life support is being pioneered in the Biosphere II Project, a complete environment contained under 3 acres of glass (see fig. 5). Billed as the most exciting scientific experiment since the lunar landing, the airtight structure will contain 20 000 square feet of farm, where all the food will be grown. There will also be a desert, ocean, marsh, savannah, and rainforest (with 3800 species from ladybugs and shrimp to fowl and deer), laboratory, library, and apartments. Eight scientists will spend 2 uninterrupted years inside the project, which is designed to simulate life in a space colony, beginning in September 1990 (Dawson 1989). Biosphere II is a private, profit-oriented project operated by Space Biospheres Ventures. Most of the $37 million for the 4-year-old enterprise has been donated by Texas multimillionaire Edward Bass (Steacy 1988). The intent is to restore environmentally damaged areas on Planet Earth as well as advance NASA's exploratory programs. Techniques under development include chemical-free farming, natural pest-removers, crop rotation, and new ways to recycle nutrients through the soil and purify both air and water. The entrepreneurs believe that an ecological industry can turn a profit and that working with the flow of nature should cost less in the long run. They expect to market the new methods and equipment they are developing.



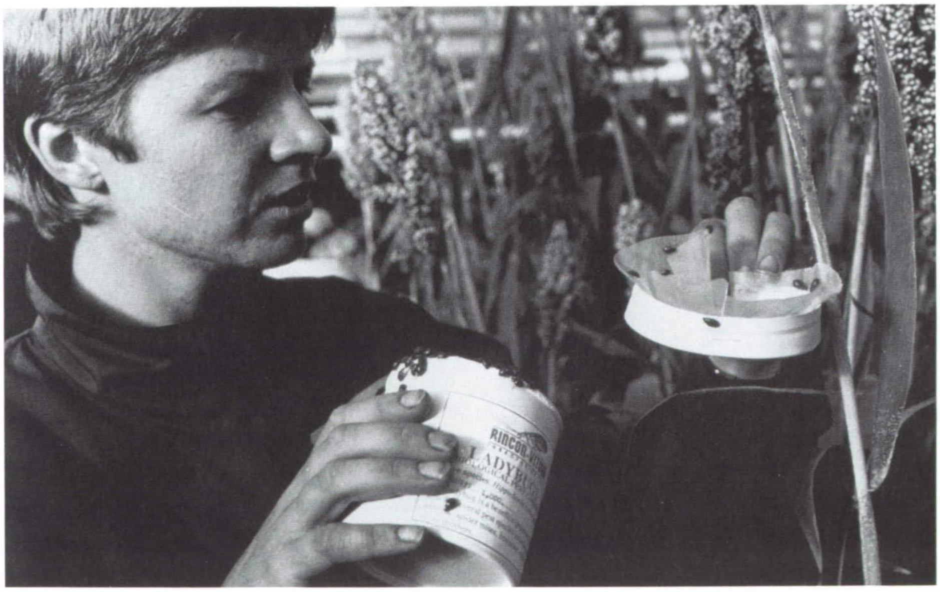


Figure 5

Biosphere II

This huge terrarium was built near Tucson with private financing in 1989 and will be occupied by a collection of 3800 species (including eight Homo sapiens*) for an uninterrupted 2-year period starting in 1990.*

The 3-acre, airtight, glass and frame structure includes five wilderness biomes. From a mountain in the center of the rainforest, a stream cascades down a waterfall and across the forest floor. It flows along a savannah, at the top of the rock cliffs, through fresh- and saltwater marshes to a 25-foot-deep ocean, which encompasses a coral reef. A thornscrub forest makes the transition between the savannah and a desert, the biome that most nearly matches the external environment.

Behind the wilderness biomes in this view are the 24 000-square-foot intensive agriculture biome and the six-story, domed human habitat biome. The natural processes in Biosphere II will be artificially assisted by two "lungs," to accommodate warm air expansion, which would otherwise blow out glass panes or break the seals, and by air and water circulation systems, because the unit is not large enough to generate weather processes.

Its developers believe that not only is such a controlled ecological life support system applicable to future space colonies but also the techniques developed such as chemical-free farming may be useful in restoring to environmental health parts of Biosphere I—our Planet Earth.

- Ecologically safe power generation can be achieved by generating power via satellites for use on the ground as well as in space. The feasibility of new solar power technologies to collect and beam power between objects in space and the Earth needs to be tested. It is not yet clear which orbits and which portions of the electromagnetic spectrum would best be used to transmit energy to Earth from space (Glaser 1989).

- Ecologically safe waste treatment can be achieved through transfer of a NASA-developed technology to Planet Earth municipalities. The NASA Technology Utilization Office, which encourages non-space applications of technology developed by NASA, transferred the first Planet Earth application of the artificial marsh filtering system (intended to treat wastewater in space colonies—research began in 1971) to a local municipality in Haughton, Louisiana, in 1986. An 11-acre lagoon and a 70- by 900-foot gravel bed with rooted aquatic plants were set up (see fig. 6). Highly effective (bacterial levels were far below permitted limits), the process was also found to be highly cost-effective (only a fraction of the cost of the conventional approach). Presently 15 to 20 systems are on-line or in the design phase throughout the United States (Dawson 1989).

Figure 6

Natural Wastewater Treatment

At Haughton, Louisiana, town officials installed a second-generation version of NASA's natural wastewater treatment system. The raw wastewater is pumped into the lagoon, where floating water hyacinths digest enormous amounts of pollutants. Then the water flows over a rock bed populated by microbes that cleanse the water further. Aquatic plants growing in the gravel bed—bulrushes in the foreground and canna lilies in the background—absorb more pollutants and help deodorize the sewage. Although water hyacinths are limited to warm climates and fresh water, bulrushes and canna lilies can tolerate both cold and salt water.

It is important to note that a rash of new product innovations could foster economic growth at levels unseen to date.

Sourcing/Manufacturing/ Distribution: Spearhead global industrial restructuring

All of our activities have environmental consequences, and all of our activities must be changed rapidly if our rendezvous with disaster is to be halted.

> The challenge facing humanity in the '90s is to reverse the environmental degradation of the planet before it leads to economic decline. . . . Meeting this challenge requires more than fine-tuning; it will take a fundamental restructuring of the global economy. (Brown 1990)

Any blueprint for an environmentally sustainable global economy would require the following.

Eliminate sources of pollution: Some pollutants have been successfully removed from the atmosphere. In each case—lead, DDT, PCBs, strontium 90—substantial improvement was achieved not by tacking a control device onto the process that generates the pollutant but by eliminating the pollutant from the production process itself (Commoner 1990).

Replace environmentally assaulting production technologies with inherently pollution-free processes: Ecologically and economically sound technologies do exist.

- If farmers would shift to organic agriculture, the rising tide of agricultural chemicals that now pollute water supplies would be reversed and food would be free of pesticide-derived carcinogens.

- If automobiles were powered by stratified-charge engines, which sharply reduce nitrogen oxide emissions, the urban pall of photochemical smog and ozone—which is triggered by nitrogen oxides—would be lifted.

- If electricity were produced by photovoltaic cells, directly from sunlight, the air could be freed of the noxious pollutants generated by conventional power plants.

- If the use of plastics were limited to those products for which they are essential, we could push back the petrochemical industry's toxic invasion of the environment. (Commoner 1990)

Consider transferring the major eroders of Planet Earth off planet: The components of growth and globalization of human activity that have had the greatest impact on the environment from 1850 to the present are agriculture, the dominant agent of global land transformation—9 million square kilometers of surface has been converted to cropland; energy, which has risen by a factor of 80; manufacturing, which has increased a hundredfold in 100 years; and basic metals, which has experienced a long-term growth greater than 3 percent per year. Each of these could conceivably be transferred off Planet Earth: agriculture, using biosphere or hydroponic techniques; energy, using solar power transmission to the Earth; manufacturing, possibly using robots on the Moon; and mining of basic metals on the Moon, asteroids, or Mars. What better justification for going to the Moon or Mars than to make life better for the Planet Earth consumer!

Eliminate indifferent public policies: Current public policies have been found to actively encourage deforestation, desertification, destruction of habitat and species, and decline of air and water quality (Clark 1989). Mechanisms, both national and international, need to be developed to coordinate managerial activities pertaining to ecologically safe industrial restructuring. Local development actions have cumulative results on the global environment that are difficult to communicate, short of demonstrating them from a vantage point in low Earth orbit. Science can help, but it is efforts that go beyond science to formulating adaptive policies that encompass environmental surprises which will ultimately determine our effectiveness as managers of Planet Earth.

Capability-Driven Innovation: The Process of Engineering Critical Technological Advances

> Science seemed at its birth to be but superfluity and fantasy, the product of an exuberant overflow of inward activity beyond the sphere of the material necessities of life, the fruit of the curiosity of dreamers and idlers. Then, little by little, it achieved an importance and an effectiveness. . . . We who live in a world which it revolutionized acknowledge its social significance and sometimes even make it the object of a cult. Nevertheless we still leave it to grow as best it can, hardly tending to it at all, like those wild plants whose fruits are plucked by primitive peoples in their forests.
> (de Chardin 1972, p. 129)

Our technological capabilities have not yet reached a level that facilitates realization of our loftiest goals. And the level of technological capability determines the effectiveness of our efforts and their cost efficiencies. We cannot mobilize a program to colonize the Moon or Mars within the next 3-5 years, for example, precisely because our current technology makes it economically infeasible. Getting materials and people into space simply costs too much; we don't know what's there—except on a superficial level—or how it can be used; and we are not sure that we can remain alive for any extended period of time, let alone return to Earth without having been debilitated in some way. The most critical impediments to space exploration are the lack of cost-effective means to leave the pull of the Earth's gravity, the availability of only a rudimentary controlled ecological life support system, and the inability to conduct research on space phenomena in enough depth to develop innovative products and processes (table 3). These are effectively the independent variables—or the problems whose resolution will facilitate a broad range of subsequent projects and programs.

TABLE 3. *Priority Issues in a Space Technology Development Program*

Independent variables	Dependent variables
Getting into space: launch vehicle economics (highly competitive)	Vehicle size Cargo capacity Fuel type
Living healthily in space: sustainable life support systems	Length of stay in space Distance travelable
Working productively in space: facility in which to experiment (ex., space station)	Development of new products & processes for commercial manufacturing Renewable power supply

Intervening variables (could significantly change the game rules)
Discovery of other life in the universe, perhaps more intelligent (and therefore having many capabilities already in hand) or distant (thus changing our target destination)
Major breakthroughs in speed of travel, perhaps rendering Mars less interesting (because we can go farther) or more interesting (because we can get there faster)
Inability to sustain life on a long-term basis outside of Earth's atmosphere, or prohibitive hardship in doing so

The National Research Council, an arm of the congressionally chartered National Academy of Sciences, believes that it is vital that Moon-Mars missions have "the capability to send humans into space, maintain them in a physical condition that permits them to work productively, and return them to Earth in good health." It has not been demonstrated that after long-duration space flight individuals can readjust rapidly to gravity without serious physiological consequences ("U.S. Panel" 1990).

One way to ensure that the effort is sustained is to make sure that the basics are in place: to focus for a time on technology development, to reduce the operational costs of spacefaring and to establish the facilities and systems—the infrastructure—that a serious program requires (Sawyer 1989). To respond to existing technology constraints, to be able to break through the current quality/cost parameters, we need to develop a targeted, thoughtful technology advancement program. A segmentation based on capabilities in hand, and capabilities required, brings to the surface the major technology gaps to be bridged (table 4). Mastery of these technologies is most likely to open up space activities to the broadest possible constituency. When the costs of getting into space, surviving in space, and producing in space are sufficiently reduced, an infrastructure can be built to nurture the wealth-generating efforts of small entrepreneurs and independent individuals, as well as major corporations and governmental agencies.

TABLE 4. *U.S. Mission Scenarios: Capability-Driven Innovation*

Capability	Technological impediments	Proposed projects/requirements
Space transportation	Economic access to space	• Shuttle C unmanned cargo version of Space Shuttle • New generaton heavy lift rocket, to lift 300 000 lb + • Aerospace plane—advanced propulsion, horizontal take-off • Civil Space Technology Institute (CSTI), to increase operating margins of propulsion hardware
	Maneuverability in orbit	• Exploration Technologies R&D Program, to develop technology for operations beyond Earth orbit • Develop two orbital vehicles • Develop in-space assembly capability • Develop system for storing propellants in Earth orbit for later use • Develop small, reusable moonship that separates into lander and orbiting module • Develop accurate and safe autonomous landing, rendezvous, and docking and sample retrieval
	Deep space travel	• Develop a rocket powerful enough to reach Mars
Advanced technology	Sufficient power supply	• Construct energy forms to beam power to Earth (NASA Lewis/Harris solar concentrator) • Develop space-based nuclear reactors (JPL SP-100; Westinghouse Multimegawatt Space Nuclear Power Supply) • Mine the Moon for alternative energy sources • Develop advanced chemical propulsion
	Automation and robotics breakthroughs	• Develop advanced "intelligent systems" technology to reduce cost of unmanned probes
	Advanced data and computer system breakthroughs	• Develop advanced computer technology to reduce cost of unmanned probes

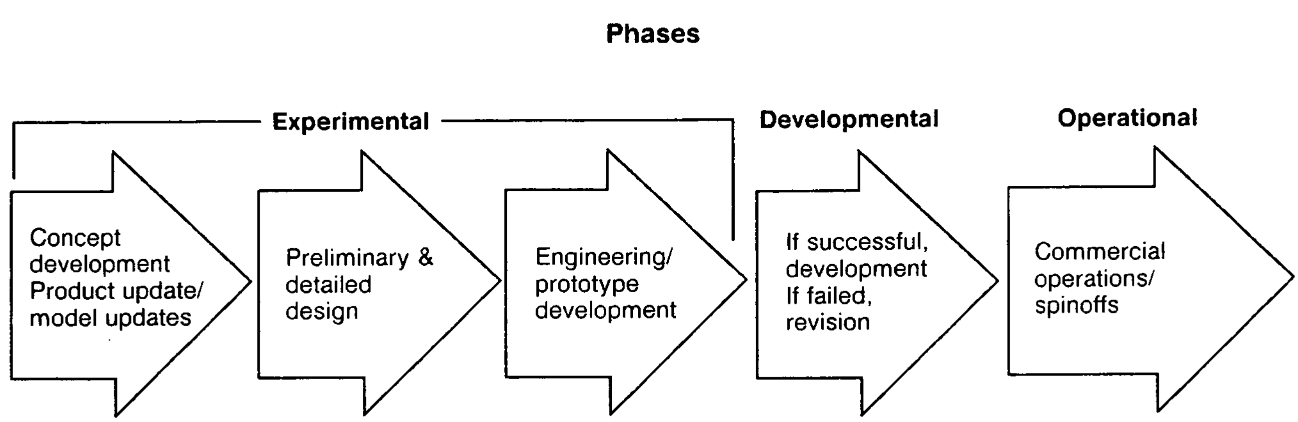
TABLE 4 *(concluded)*.

Capability	Technological impediments	Proposed projects/requirements
Life sciences	Substitute gravity	• Modify the impact of microgravity on human systems by exercise, artificial gravity, autogenic feedback training, and nutrition (NASA Ames) • Understand interdependence of musculoskeletal, cardiovascular, and endocrine systems in low and artificial gravity (Space Station *Freedom*) • Determine the effects of extended weightlessness on humans
	Sustainable food supply	• Experiment with hydroponics space farm that uses nutrient-rich solutions instead of soil • Develop self-sustaining system from growing fruits and vegetables in space
	Closed water/waste treatment system	• Biosphere II, a complete environment under 3 acres of glass • Controlled ecological life support system (CELSS) • Bioregenerative life support to generate oxygen, supply fresh food, remove excess carbon dioxide
	Shelter	• Develop building materials and alloys from lunar ore • Test use of spherical inflatable housing structure made of Kevlar (Lawrence Livermore Natl. Lab)
	Oxygen	• Extract oxygen from lunar materials for use in life support systems and as propellant
	Remote health care	• Develop clinical health maintenance facility

Sources: Berry 1989; Covault 1989d; "Gardens in Space," Los Angeles *Times* 4-2-89; Harford 1989; Henderson 1989; Sawyer 1989; Westinghouse 1989.

The funding requirements to achieve such technological advances are difficult to estimate: A dichotomy exists between the cost to make the leap and the cost savings achieved as a result of the leap. Since the breakthrough has not yet been achieved, it is impossible to predict how many false starts must be surmounted in the struggle up the learning curve to success (table 5). Such development does not necessarily follow a straight line; it is often a series of iterations, evolutionary in its unfolding. Because these "technological leap" projects cannot even guarantee that success will be attained, they are by definition high-risk. However, achievement of the breakthrough provides enormous rewards to the technology owner and permanently redefines the competitive arena to the advantage of the breakthrough innovator. Because the efforts are often very expensive, they are increasingly undertaken on an industry-wide basis; because the results can be very lucrative, they are often kept secret from other nations—guarded like the national treasures they are.

TABLE 5. *The Life Cycle of a Technological Breakthrough*



Cost exposure can be reduced through partnerships among government agencies, industry, academia, and entrepreneurs from the same country—or via international partnerships. When a government participates in a project, supported by public financing, the results of the activity are typically in the public domain. Alternatively, government agencies may fund corporations and entrepreneurial companies conducting research and developing products, often with the understanding that what they learn in the process can be privately held and spun off into commercial products.

A review of the national space development strategies of selected countries reveals that while the United States is launching initiatives in a broad range of arenas (manned and unmanned), most of the other major participants, with the exception of the Soviet Union, have restricted their immediate goals to profitable commercial applications while seeking independence in space as a long-term objective (table 6). This suggests that European, Japanese, and other participants are viewing space development from a highly competitive, commercial vantage point. While they are seeking full autonomy in space, they are willing to joint venture in the short term (they say) in order to catch up. Overall, space is viewed as a terrain in which major technological leads can be developed and sustained.

TABLE 6. *National Space Development Strategies: A Comparison*

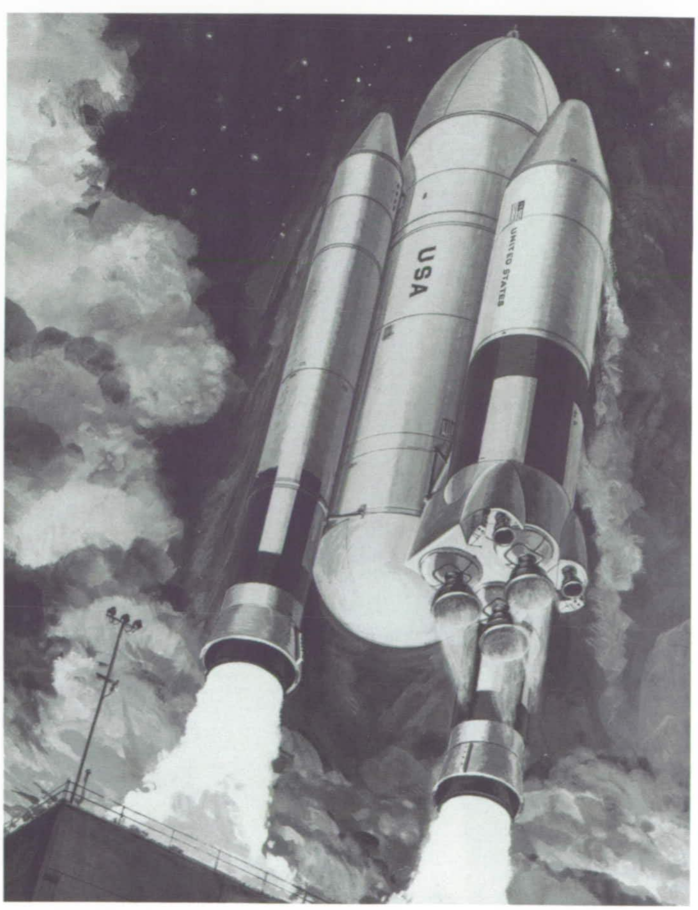
Country/agency	Focus	Philosophy	Strengths/weaknesses
U.S.A./NASA	Unmanned exploration Manned spacefaring	Massive technological leaps in R&D objectives	Bush commitment to take a fresh look Continually changing vision/funding
U.S.S.R.	Put man on Mars within next 25 years	Gradual development of space capabilities	Management sharply criticized
Europe/ESA	Propulsion technologies	Full autonomy in space by year 2000	Reluctant to commit financing Has technical ability to be a major space power but seems to lack political will required to achieve most cost-effective results
Japan/ NASDA ($1.1 billion) Institute of Space & Astronautical Sciences ($114 million)	Commercial-ization	Good space science doesn't need to be expensive	Heavily subsidized by Japanese private companies A late start because no military expenditure, but reshaping program for 1990s
Canada/Canadian Space Agency ($1 billion +)	Robotics	Cooperate to participate in new technology development	Robotics a Canadian strength Target strategic technologies that make possible the mission-critical mobile servicing system
India/Indian Space Research Organization (ISRO)	Commercial-ization	Attract industry through divesting management & technical operation of selected facilities to industry	Guarantees 15% profit margin on projects Encourages honing technical skills Deemed "export," entitles suppliers to huge tax concessions

Sources: Bennett 1987; De Cotret 1988; Gibson 1984; Kapur 1987; Lenorovitz 1988a, b, c; "Soviets Put Craft," New York *Times* 1-30-89.

This focus on capability development may appear low-key to the general public when compared to more visible Moon or Mars projects, because it is technology-centered and forces repetitive iterations to uncover the product or process dynamics in enough depth to engineer a major innovation. However, our success in advancing our capabilities will ensure the smooth implementation of those more visible, destination-focused projects.

Getting Into Space: Propulsion

The single most frustrating problem related to space development is the prohibitive cost of getting vehicles, materials, and people into space. Once out of Earth's gravity field, there are additional issues regarding maneuverability and propulsion through deep space. The pace of commercialization, however, depends on the pace of the launching business.



Concept for a Heavy Lift Launch Vehicle Derived from the Space Shuttle

By replacing the Shuttle's manned orbiter with a cargo carrier, the payload capacity of the space transportation system can be increased by 2-3 times over current capacity per launch. Costs should also be lower.

Figure 7

Concept for the National Aerospace Plane

Artist: Stan H. Stokes (NASA Art Program Collection)

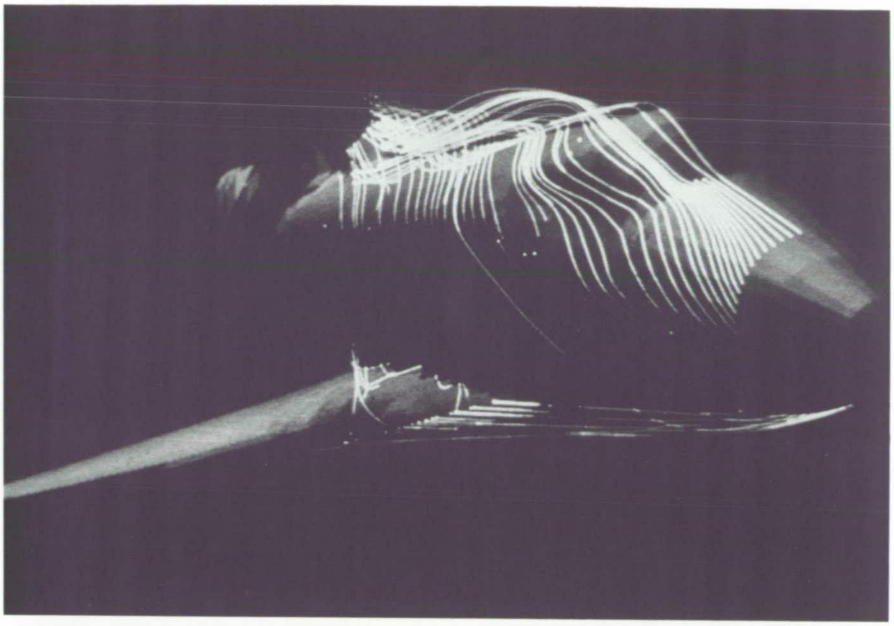
Technologies developed for the national aerospace plane (and spinoffs from that technology development) would greatly improve the competitive position of the United States in the aerospace field. This revolutionary class of vehicles would be able to take off and land horizontally on standard runways like a conventional airplane, cruise in the upper atmosphere at hypersonic speed, or fly directly into Earth orbit.

Its "scramjet" engines would burn a mixture of hydrogen and air, thus obviating the need to carry liquid oxygen. Its horizontal takeoff and landing (HOTOL) capability would eliminate the need for vertical launch facilities currently required for the Space Shuttle and unmanned boosters. These two capabilities should allow the spaceplane to deliver payloads to orbit at a fraction of today's cost.

The technologies are applicable to supersonic (above Mach 2, or 1300 mph) military transports and hypersonic (above 4000 mph) civil planes that could fly passengers from the United States to Japan in 2 hours.

The phase of the joint Department of Defense/NASA effort which began in 1986 involves development of key technologies in propulsion, aerodynamics, advanced structures, high-temperature materials, and computational fluid dynamics. Computer simulation is used to "fly" mathematical models of the national aerospace plane, which must attain 17 000 mph (Mach 25) to escape Earth's gravity and reach orbit.

Experimental—skills beyond a single organization: The most impressive propulsion project being developed today is the national aerospace plane (see fig. 7). Regarded as of profound strategic urgency, it is expected to have a major effect on the course of U.S. space and aeronautics development into the 21st century as well as a tremendous impact on American competitiveness in the aerospace field, which is our number 1 export category. A direct counter to similar efforts under way by the Europeans, the Japanese, and the Soviets, it is expected to be completed by 1997 (3 to 5 years ahead of the others).



Particle Tracings Over the Space Shuttle Imaged by NASA's Numerical Aerodynamic Simulator

The effect of hypersonic airflow upon such vehicles cannot be tested in wind tunnels, which go no higher than Mach 8. NASA's Numerical Aerodynamic Simulation Facility, located at Ames Research Center, is using Cray supercomputers to build to an eventual capability of 10 billion calculations per second. Such computational capability will not only provide enormous impetus to aerospace development but also permit major advances in other structural design, materials research, chemistry, and meteorology.

A team of private industry contractors is sharing development costs with the Government and operating as a noncompetitive consortium to share research data, keep costs down, and quicken the pace of technology.

The national aerospace plane is sure to be a major technological leap if achieved, because never before has an experimental aircraft been designed to fly so much faster and higher than any other plane (Covault 1989a). Its design parameters are to

- Achieve a speed of 17 000 mph to escape Earth's gravitational pull and reach orbit
- Circle the globe in 90 minutes
- Withstand a temperature of 3000°F
- Have engines designed to gulp oxygen from the air
- Determine the effect of hypersonic atmospheric chemistry (Lavin 1989)

Clear standards of cost-effectiveness have been defined for the national aerospace plane:

- Must be cheaper to operate than the Shuttle and require less manpower
- Must be able to use any standard airport in the world (Lavin 1989)

What is remarkable about this program is the extent of national-level, industry-wide collaboration focused on this critical technological breakthrough. Truly the best skills have been brought to bear on the task. The project team includes NASA, the Pentagon, and five U.S. aerospace companies led by the Air Force (three airframe manufacturers and two engine manufacturers). In effect, all of the major competitors in the aerospace industry have been invited to participate equally—on a level playing field. Take the development work for the heat-resistant material: None of the companies could afford to do all the research alone, so each has specialized in one type of material, sharing the results with all competitors. Discussions are under way regarding ways to collaborate in building the plane itself (Lavin 1989).

What is alarming is that our leadership in this area is not secured, and major competitors have set their sights on the same goals. The European Space Agency, representing 13 European countries, has a three-pronged space program that includes a fifth-generation Ariane heavy lift rocket, a module of Space Station *Freedom*, and three versions of the horizontal take-off and landing aircraft (table 7). This horizontal take-off technology is regarded as so critical that the Europeans cannot agree on who should lead the project, where it should be headquartered, or how it should be engineered.

TABLE 7. *European Space Agency: Three-Pronged Space Program**

Program		Scope	Participants		Est. budget
Ariane V heavy lift rocket		Liquid hydrogen & oxygen fuel Max. load 100 000 kg Will double launch capability	France W. Germany Italy Others	45% 22% 15% 18%	$3.5 billion
	Hermes piloted spaceplane	Target launch 1996-7	Avions Dassault-Breguet (engineering) Aerospatiale (coordination) (45% French funding)		$4.4 billion
"HOTOL" (Horizontal Take-Off & Landing) (three alternatives)	U.K. alternative	Upgraded version of Concorde: horizontal take-off, air-breathing engines to boost to near vertical trajectory, horizontal return	British Aerospace		
	Sanger (W. German alternative)	A small reusable spacecraft launched from back of aircraft, reaching orbit on own power, then gliding back to Earth	W. German aerospace companies		
Columbus Space Module		Part of U.S.A.-led int. space station project	13 member states		$3.7 billion

*ESA is reluctant to commit to all three key space projects.

Sources: Dickson 1986, 1987; Mordoff 1988.

Developmental—synergies and interfaces: The United States is ahead in low-cost rockets for small payloads, thanks to Orbital and other small entrepreneurial organizations. Orbital Sciences Corporation developed a 50-foot, winged rocket, the Pegasus, and launched it from a B-52 flying over the Pacific Ocean. (See figure 8.) Pegasus' winged design is a first for unmanned rockets, giving the vehicle the extra lift it needs to head toward orbit most efficiently from a horizontal airborne launch. Developed to address the needs of "microspace" (that is, smaller and more affordable rockets and satellites), it is intended to launch "lightsats," a new class of satellites. The objective of this highly focused development strategy was to provide space-oriented products and services that appeal to a wider group of governments, companies, and entrepreneurial consumers. This down-sizing effectively reduces the cost per pound of payloads in orbit, a critical factor in developing a broader based commercial space industry.

Figure 8

The Pegasus Rocket

Designed and built by Orbital Sciences Corporation and Hercules Aerospace Company and sponsored by NASA and DARPA (the Defense Advanced Research Projects Agency), this 50-foot-long, winged rocket is carried aloft by a B-52 before the first of its three motors is ignited. Its down-sizing is intended to offer much lower cost for the delivery to orbit of lightweight satellites.

Once Orbital's rocket is made operational, the company expects to sell commercial launches for $6-7 million or $6000 per pound of payload (versus $20 000 per pound for small satellites carried by other lightweight payload rockets, such as the Scout rocket by LTV Corporation). It is important to observe the amount of Government support required for such entrepreneurial efforts: The Pentagon's Defense Advanced Research Projects Agency (DARPA) paid $6.5 million to Orbital for the launching, making the project economically feasible, and NASA provided the B-52 for the launch, effectively establishing the credibility of the provider. NASA and DARPA are considered to be anchor customers—the largest and most sophisticated consumers of space products, consumers whose needs create the demand for, and define the parameters of, new products and processes to be developed (Stevenson 1990).

Operational—indicators of success: The unmanned vertical rocket launch business is an established technology, in an established industry, with heavy global competition. A $2 billion worldwide industry, the commercial launch of satellites is forecast to continue to grow through the 1990s. As communications networks are being privatized and deregulated worldwide, even more activity can be expected (Cook and Lewis 1988).

There have been two keys to success in operating a launch business:

- The right product

Europeans believed that unmanned launchers such as Ariane would continue to offer the better solution for launching satellites that do not require the presence of astronauts. The primary goal of Arianespace was to give Europe an independent launch capability for its own satellites (Dickson 1986), but the result has been to provide a competitive advantage in the international marketplace (Lenorovitz 1988a, b, c). Ariane of Arianespace has averaged about a 50-percent share of the global launch market, also taking a share from the Space Shuttle after the *Challenger* disaster. Forty-three satellites were launched between the beginning of Ariane's commercial program, in 1981, and 1990. More than 32 launches are scheduled, as of February 1990, at a value of $2.36 billion. Launches have been suspended twice: once in May 1986 and again in February 1990, both times to allow for inquiries into explosions of rockets in flight, destroying their satellite cargoes ("Panel To Examine" 1990). Ariane must adhere to a rapid and sustained launch rate if it is to fulfill the orders currently on its books and to compete for new business.

• The right price

The Space Shuttle, a manned vertical launch vehicle, was expected to command 75 percent of the global launch business when envisioned by Nixon in the 1970s. We were first in a market that was wide open—but with the wrong price parameters. The lower the launch cost, the broader the customer base. However, we somehow got locked into a technology that is not cost-effective. Although it has been a superb research vehicle and it has taught us how to design a reusable reentry vehicle that could bring material back from space, the overriding reason it was built was to lower costs. *Reusable* has turned out to mean "uncorrectable." The Shuttle's overhead cost is $3 billion a year, excluding the hidden costs in salaries (10 000 people are required at Cape Kennedy to launch it). At only eight or ten flights a year, the cost is at least $300 million per flight (Brown 1989). After the *Challenger* accident, President Reagan determined that private companies would handle all commercial launches (Peterson and Schares 1988).

Three U.S. companies (McDonnell Douglas, Martin Marietta, and General Dynamics) are going head to head with companies abroad for business (see table 8) and have occasionally enjoyed a cost advantage depending on the changing value of the dollar. Ariane is considered to be an equal competitor with the United States in heavy-launching capacity, and the Japanese are catching up fast.

TABLE 8. *Worldwide Commercial Launch Market, a $2 Billion Space Transportation Industry*

Company	Rocket	Payload capacity, lb (kg)	Cost/launch, $ million	Success rate, %
McDonnell Douglas	Delta II	4 000 (1800)	50	98
Martin Marietta	Titan III	10 000 (4500)	110	96
General Dynamics	Atlas-Centaur	5 200 (2400)	59	95
Ariane	IV	9 200 (4200)	85	80
China	Long March 3	4 000 (1800)	35	
U.S.S.R.	Proton	4 800 (2200)	36	
Japan	(Will begin competing in 1993)			

Sources: Cook and Lewis 1988, Feder 1900, Peterson and Schares 1988.

Price competition is stiff. For example, China typically beats Ariane's satellite launch price by several million dollars and usually agrees to underwrite $30-60 million insurance on the launch for a premium 15 to 20 percent below world rates (Peterson and Schares 1988) as a way of buying a larger share of the market.

Living Healthily in Space: Full functioning

Human spacefaring is only worthwhile if it is a peak experience—that is, if really challenging and creative work can be done in space. For humans to be as productive in space as they are on Earth, their life support system must be totally integrated, leaving individuals whole and intact, so that their functions are not in any way impaired.

Life Sciences received only $124 million of NASA's $13.3 billion budget for fiscal year 1990. Without understanding the scope of research required to resolve the critical issues, it is difficult to say whether that is too little or too much. At first glance, however, it appears that life support research is less advanced than other areas of space engineering and science.

Life support: To date, it has been possible to send astronauts into space with a full stock of expendables such as air, water, and food without regeneration because of the short timeframes of the missions undertaken. Since resupply would be impossible at a location like Mars, which is 2-3 years away from Earth, resources would have to be reclaimed and reused more and more, or else mined, grown, or otherwise produced onsite. Work is under way on a partially closed air and water system for the space station, which may be sufficient for initial trips to the Moon and Mars. It may be desirable to extend the system to a self-monitored and self-controlled ecological life support system that turns metabolic and other waste into food, potable water, and a breathable atmosphere by integrating biological, physical, and chemical processes (Aaron et al. 1989).

A controlled ecological life support system (CELSS) program was initiated by NASA in the late 1970s. The long-term goal is to devise a bioregenerative support system to generate oxygen, supply fresh food, and remove excessive carbon dioxide from the station. By reducing the amount of expendables that must be carried into space, the system is expected to lower operating costs. Essentially, CELSS uses biological systems to recycle air, water, and waste products (Hubbard 1989). A physical/chemical version of this system is planned for Space Station *Freedom*. This system will recycle the water and air supply using nonbiological technology. A more advanced system which incorporates plants and food production is being explored for Moon and Mars missions.

Initial cost in terms of mass lifted into orbit will be high; but, since it is expected to function indefinitely and since it will pay for itself (that is, generate food and oxygen equal in mass to the mass of the system) in 5-7 years, the system is expected to have minimal costs over its lifetime. A benefit of a bioregenerative system is its ability to provide psychological comfort as well as supply fresh food to crews who are isolated from the Earth for a long time. Research continues on recycling, system stability, and food production (Hubbard 1989). NASA has awarded grants to universities and research centers to experiment with growing such crops as wheat, lettuce, white potatoes, sweet potatoes, soybeans, sugar beets, and peanuts under weightless conditions and under different types of artificial light ("NASA Seeks" 1988).

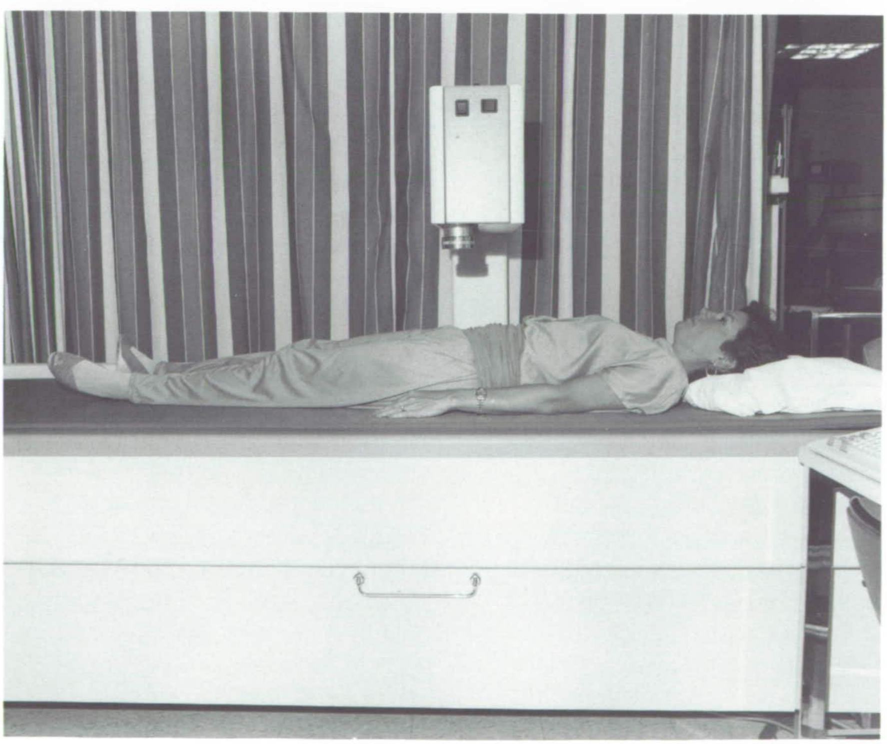
Lunar Greenhouse

Such a bioregenerative life support system might provide psychological comfort, as well as fresh food, water, and air, to crews isolated from the Earth for a long time.

Courtesy of the artist: Robert McCall

Gravity: Only one man, Yuri Romanenko, a Soviet cosmonaut, has ever been in orbit for close to a year: He took a 326-day mission in 1987. His condition upon return was quite alarming. He had significant loss of skeletal bone; he lost 15 percent of muscle volume in his legs—enough to require him to relearn to walk—despite exercise; and there are serious concerns about his heart.

Although the human body responds to microgravity with neurovestibular changes that can cause astronauts to suffer temporary disorientation and sickness during a mission, there are more serious musculoskeletal and cardiovascular effects such as loss of muscle mass, bone decalcification, and blood pooling that can cause problems in flight and after the astronauts return to gravity. Exposure to space produces biochemical and physiological changes in plants and animals from the cellular level to the whole organism.



Bone Densitometer

This total body bône densitometer measures the total calcium in the human body. Loss of calcium has been seen in astronauts and cosmonauts who have experienced weightlessness for more than a few days. Such a loss has also been observed in subjects in bed rest studies (the conditions of which may more nearly resemble the reduced gravity of the Moon). The Medical Sciences Division at the Johnson Space Center is studying ways to reduce the calcium loss in space by giving subjects exercises to perform or medication or both.

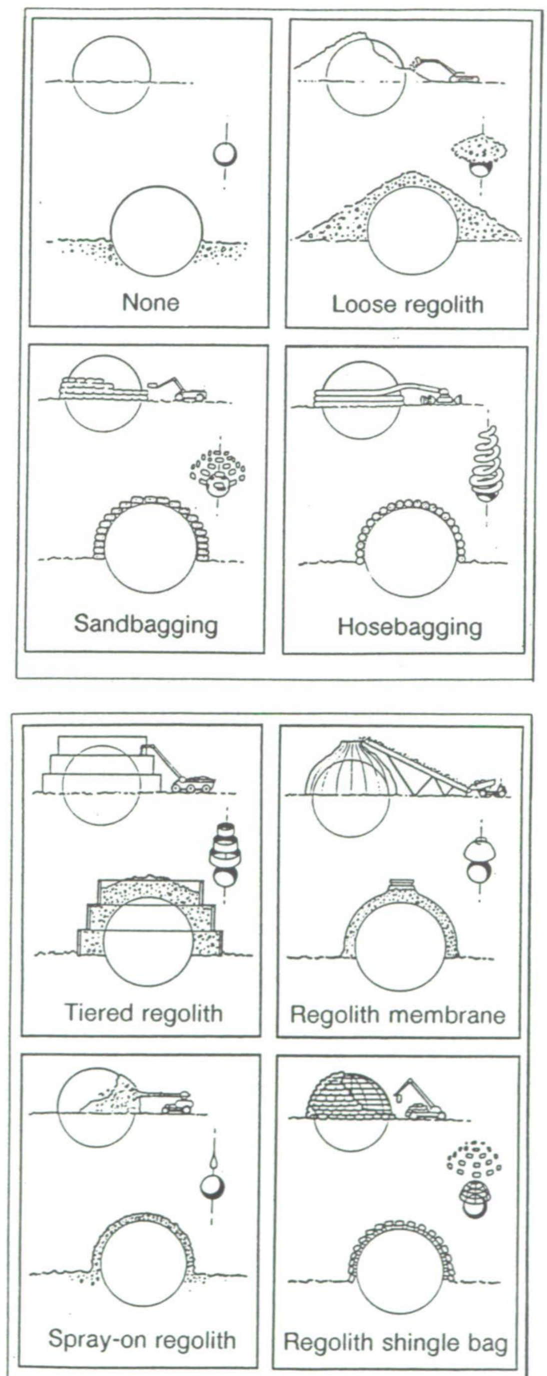
Space Station *Freedom* will have a life science research facility that will include a centrifuge system (1.8-2.5 meters in diameter) that produces an environment with gravity levels of 0.01-2.0 *g*. This is a first step in a program that requires acceleration devices in order to analyze the effects of microgravity and varying levels and exposure times of linear acceleration on biological systems (Hubbard 1989).

There are now serious doubts that humans can work effectively or efficiently in weightlessness for longer than 4 to 5 months. Humans cannot stay weightless in space more than about 12 months without risking permanent physical damage (Banks 1989). Since the shortest Mars trip will take 14-17 months, and the more efficient trips will take 3 years, advanced countermeasures are a must. They will probably include artificial gravity created by rotating the entire vehicle or by using a local centrifuge. Areas of further study on artificial gravity include temporary versus constant exposure, radius and rates of rotation, and the associated *g* loadings, side effects, and problems of transition between nonrotating and rotating environments (Aaron et al. 1989).

A goal of NASA's Ames Research Center is to extend the presence of humans in space. A growing body of data reveals an interdependence among the musculoskeletal, cardiovascular, and endocrine systems. There is an emerging interdisciplinary approach at Ames which recognizes the interrelationship of physical forces, gene expression, metabolic processes, and hormonal activity. Biomedical research, human performance, and life support systems form the core of the Ames program. How the effect of microgravity on human systems can be modified by exercise, artificial gravity, autogenic feedback training, and nutrition is under study (Hubbard 1989).

The space station's clinical health maintenance facility includes basic diagnostic and therapeutic equipment both for use in near-Earth orbit and for gauging the more demanding medical implications of exploration missions (Aaron et al. 1989).

Shelter: Shielding systems must be developed for flight as well as at the destination points. Travelers to Mars would face ionizing radiation, mostly galactic cosmic rays in interplanetary space, and might experience severe proton flux from occasional solar particle events. Shielding must protect the crew in flight, whereas burrowing or placing bags of soil atop habitats will probably protect explorers on the martian or lunar surfaces (Aaron et al. 1989).

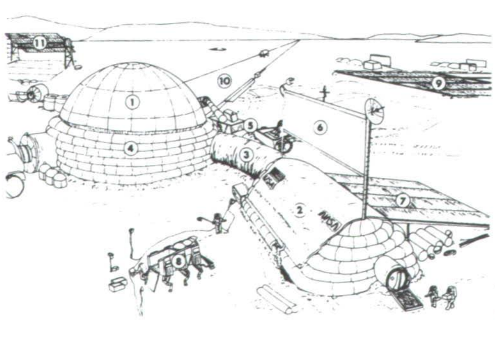


Options for Habitat Radiation Shielding

Dr. Lowell W. Wood and his group at Lawrence Livermore National Laboratory suggest building inflatable spacecraft for space stations and a Mars probe instead of the rigid metal variety now planned. The use of inflatables accounts for part of the cost savings asserted by the LLNL proposal. The drawback is that these systems would be used without testing in space and thus the risks to the crew would be much higher.

Producing in Space: Commercialization

The U. S. Commerce Department projects that space venture



1. The inflatable habitat
2. The construction shack
3. Connecting tunnel
4. Continuous, coiled regolith bags for radiation protection
5. Regolith bagging machine, coiling bags around the habitat while bulldozer scrapes loose regolith into its path
6. Thermal radiator for shack
7. Solar panel for shack
8. Experimental six-legged walker
9. Solar power system for the outpost
10. Road to landing pad
11. Solar power system for the lunar oxygen pilot plant

Lunar Outpost

In this artist's concept of the lunar outpost described in NASA's 90-Day Study, the construction shack (foreground right) has been used as the initial habitat while the larger inflatable dome habitat was put into place, inflated, outfitted, covered with regolith for radiation shielding, and provided with solar power. In the concept proposed by Lowell Wood and his group at Lawrence Livermore National Laboratory, by contrast, the inflatable comes with all its contents already inside. It inflates automatically, and all the interior structure simply unfolds to provide rooms, plumbing, electrical circuitry, and furniture.

Artist: John Michael Stovall

revenues will be about $3.3 billion per year, with a real growth of 10 percent per year. Except for communication satellites and possibly launch vehicles, commercial space development is expected to be further down the road. The Japanese project a similar market size in the near term; they believe that the market for made-in-space semiconductors, alloys, glass, ceramics, and biomedicines will top $3.5 billion per year. But they foresee considerable growth by the year 2000, perhaps even hitting $24 billion (Buell 1987).

It doesn't make sense to explore space with manned missions unless those missions hold an ultimate possibility of becoming wealth-creating. The space industry, as an infant industry, is extraordinarily high in risk and low in short-term return. NASA has taken important steps to nurture commercial interest in the program. This is essential to converting technological insights into spinoff products and processes, as well as having the network in place to support future development and expansion.

Policy formulation: NASA introduced its Commercial Space Policy (CSP) in 1982 to reduce the risks of doing business in space and to establish new links with the private sector in order to increase development. Concerns addressed by the policy included rising insurance costs, safety, and competition from the commercial interest of other space programs, such as ESA's Ariane (Lamontague 1986).

The Reagan Administration designated commercialization a basic element of the U.S. space program. A major administrative concern was to create mechanisms for ensuring fairness for companies, users, and consumers who will be entering the space business in the future. To foster a new private-sector space industry, such policy approaches as privatization, marketing of privately owned technology currently used exclusively by the Government, private development of new technology with major assistance from the Government, and private development of new products and services without major governmental assistance were introduced (Levine 1985).

Entrepreneurial seeding: U.S. business had been confined to the role of Government contractor from NASA's inception until 1984, when the Office of Commercial Programs was formed. Since then, more than half of the 50 largest U.S. industrial corporations have been participating in NASA-sponsored commercial space activities. NASA has also established an enormous technology transfer network and developed numerous joint contractual arrangements that offer flight time for applied industrial research and development (Switzer and Rae 1989). This vital role played by NASA in partnership with the private sector has enabled the U.S. program to keep ahead.

The NASA Center for Advanced Space Propulsion at the University of Tennessee Space Institute near Tullahoma is one of 16 proposed research centers to receive $5 million per year from NASA for 5 years as startup capital, after which the centers are to be financially self-sufficient. Initially focusing on studying access to space, the U.T. consortium includes

- Auburn University
- Princeton University
- University of Alabama, Huntsville
- Air Force's Arnold Engineering Development Center
- Boeing Aerospace Co.
- Calspan Corp.
- Rocketdyne
- Saturn Corp.
- Symbolics, Inc.
- Technion, Inc.

The objective of these planned consortia is to boost the United States into a competitive posture in the commercial use of space in the next century (Mordoff 1988). The early years are expected to be more research than manufacturing, with new products and processes needed for private ventures in space expected to evolve from these research efforts. To make commercialization of space more attractive, longer range projects are also planned in areas that businesses need, such as creating vacuums and growing crystals (Feder 1990).

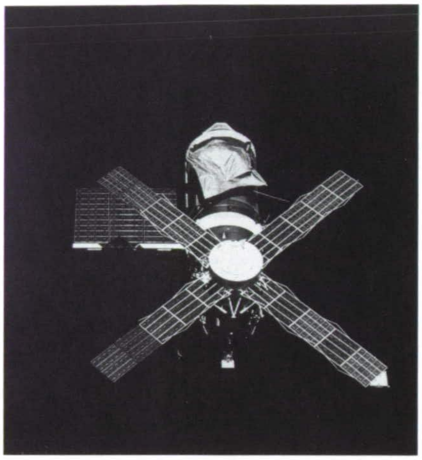
The United States is not alone in stimulating private participation: The Europeans and the Japanese are aggressively seeking opportunities to develop and provide products and processes to the global space industry.

Intospace GMBH (Hanover, West Germany), the most active and important of European space companies, is a consortium of 94 European industrial investors, mainly German giants such as Krupp, Hoechst, and Daimler-Benz. This consortium has $3 billion to spend on commercializing microgravity research (Peterson and Schares 1988). Intospace is evaluating participation in the Cosima flights' protein crystal growth missions, as well as two other research missions—Suleika (space processing of superconductive materials in microgravity) and Casimer (catalyst materials) (Mordoff 1988).

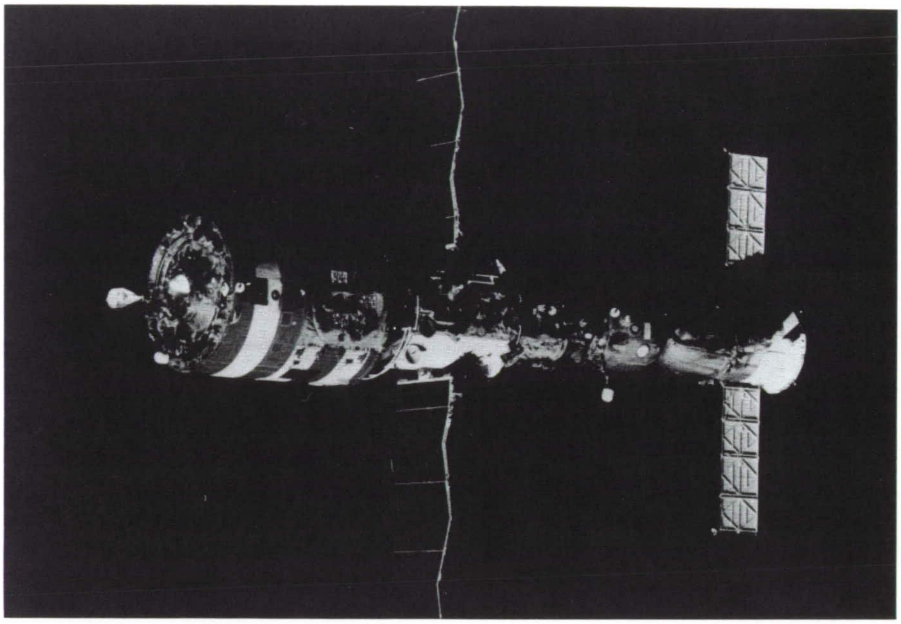
Nippon Electric Company, Mitsubishi Electric, and Toshiba, each a $15 billion plus company and a vertically integrated maker of microelectronics, computers, telecommunications equipment, and other high technology products, previously relied on government contracts and U.S. technology to expand their satellite-related business. Now they are using their own capital and forming partnerships to develop their own products (Davis 1989).

Access: Although only in low Earth orbit, a network of space stations is emerging that will enable live testing of experimental material and technologies, hopefully enabling definitive progress in the critical technology areas blocking our advancement in space. Space Station *Freedom*, a $30 billion, 500-foot U.S. craft consisting of nine pressurized modules and requiring 31 shuttle flights to loft modules, support structures, solar panels, station equipment, and supplies into orbit, will begin assembly in 1995, with completion expected in 1999. Five times the length of the Soviet Mir station, it is a spacecraft, a work station, and an experimental prototype to research products and processes. "It's the first time anything of this magnitude has been attempted by the human race"—Dr. William F. Fisher, astronaut (Broad 1990c). It will house astronauts doing scientific experiments (serving as a research laboratory) and it is currently being regarded as a way station for voyages to the Moon and Mars (serving as a transportation node).

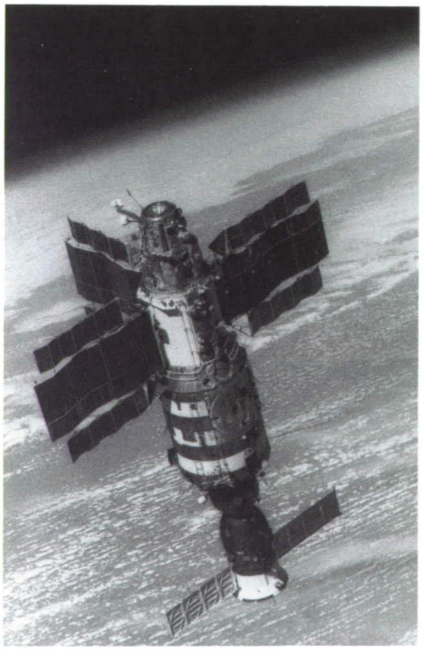
Space Stations



Skylab, launched May 14, 1973; occupied three times during 1973 and 1974; fell back into the atmosphere July 11, 1979

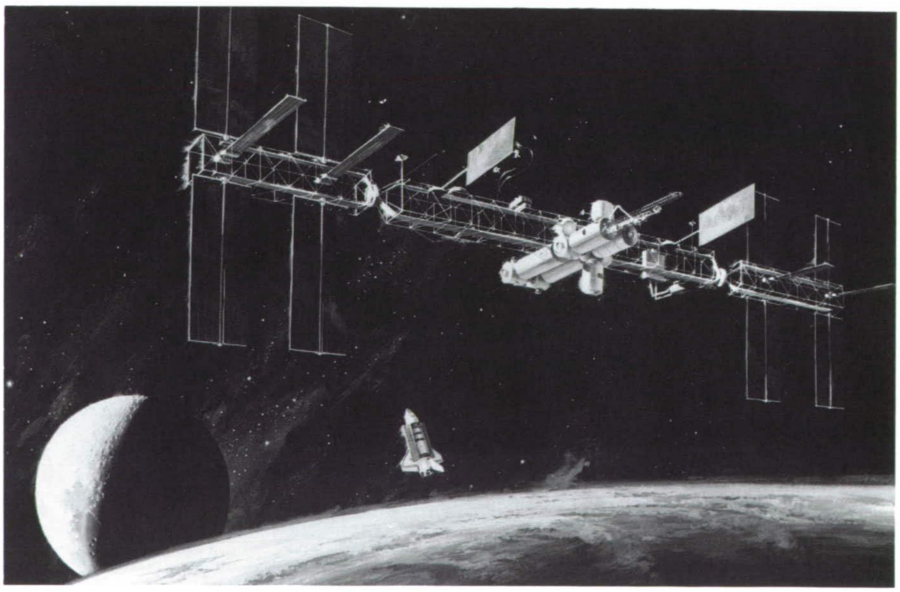


Salyut, with a Soyuz spacecraft docked on its left



Mir, with a Soyuz spacecraft docked below it

Photo: Novosti Press Agency



Freedom

Artist: Vincent di Fate (NASA Art Program Collection)

The near-zero-gravity environment aboard the Space Shuttle and at the space station was expected to lure producers of chemicals, semiconductors, pharmaceuticals, metals, and many other products to sign up or begin negotiating research agreements ("The $30 Billion Potential" 1984). Such basic research interests have not materialized to date. However, as the space industry in general begins to evolve, economic rationale for such basic research might still develop.

The United States has gotten leverage from the Space Shuttle and the space station to date on intergovernmental levels. For example, the Japanese space agency, NASDA, and NASA are sharing the cost of equipment and have agreed to share data obtained from an International Microgravity Lab (IML-1) to be flown on the Space Shuttle *Columbia* in early 1991. The series of cooperative experiments includes developing a new conductive material and investigating potential use of microgravity in making new alloys, semiconductors, and pharmaceutical products not manufactured on Earth (see table 9 for other examples).

The Soviet Mir space station, a 100-foot-long flying laboratory, is nearing completion of the first phase of construction of a 20-ton module (Broad 1990). *Mir* has a readily accessible lab, available on a rental basis to foreign astronauts and scientists as an orbiting factory, observatory, and observation post from which Earth's changing environment can be studied. The Soviets have demonstrated the ability of humans to live and work in orbit for up to 7 months. The Soviets have more in-space experience than any other nation (see table 10); however, their program has some serious coordination problems. The Soviets have underestimated the complexity of the job. On-orbit assembly has been harder than expected. Half of their instruments are not yet operational and have not been fully tested (Broad 1990c). Crews lose time on repairs and technical work, and *Mir* is too small, as it is stuffed with equipment. Nevertheless, of all participants in the space industry, the Soviets share our vision of moving beyond low Earth orbit and have the stature, in terms of in-hand technology, to do so.

TABLE 9. *U.S. Leverage Derived From Infrastructure Development: International Cooperative Efforts*

Project/ launch	Participants	Scope	Leverage for U.S.A.
Int. Micro-gravity Lab (IML-1) Early 1991	NASA, U.S.A. NASDA, Japan	Series of cooperative experiments to develop new conductive material: Investigate potential use of microgravity in making new alloys, semiconductors, & pharmaceutical products not manufactured on Earth	Share cost of equipment, share data obtained
Spacelab sharing	NASA, U.S.A. ESA, Europe Australia Canada Israel (invited by NASA)	Use Spacelab free of charge Non-U.S. provide equipment for	Equipment provided by others, share data obtained experiments
Japanese Satellite Geotail Launch at Kennedy Space Center (1992)	NASDA, Japan NASA, U.S.A.	Largest joint U.S./Japanese space program: 80% Japan, 20% U.S.A. To measure the Sun's energy flow in the Earth's magnetic field	U.S. technology & facilities in exchange for Japanese financing & assembly
Space Station *Freedom* (1995)	NASA, U.S.A. ESA, Europe Canadian Space Agency NASDA, Japan	Build orbiting S.S. *Freedom*	Build larger facility than possible independently, share data

Sources: Moosa 1989, NASA 1988.

TABLE 10. *Soviet Union Space Development Program: Strengths and Weaknesses*

Areas of strength: in-space experience

- The U.S.S.R. launches 90 to 100 spacecraft yearly, on a regular basis.
- 80% of the active satellites orbiting Earth belong to the U.S.S.R.
- Soviet cosmonauts have flown in space more than twice the hours of American astronauts and hold the record for human endurance in space.
- Space Station *Mir*, while smaller than Space Station *Freedom*, is in orbit already, and occupied. The U.S. space station will be functional in 8-10 years.
- The Soviets launched Energia, a new heavy lift vehicle, in May 1987, a significant technological step. The Energia is capable of launching 100 tons into Earth orbit—4 times the Space Shuttle payload and 5 times the U.S. rocket payload.
- The U.S.S.R. launched 200 payloads into space between 1985 and 1987—10 times the number of the U.S.A.

Areas of weakness: program coordination

- The 1990 mission with the Energia launcher has been cancelled, creating a gap of more than 2 years between heavy lift vehicle flights. It has been rescheduled for 1991.
- The aerospace industry is so decentralized that scientists and other space mission planners are excluded from participation in critical spacecraft development.
- The Soviet 1994 Mars lander-balloon mission is 5 years away from launch but still has not been fully defined.
- Two Phobos Mars missions failed.
- Changes have to be made in the design, software, and quality control of the dominant unmanned segment of the program to overcome the delays and failures of the last 2 years.
- Shuttle development took expertise away from the rest of the program.
- The U.S.S.R. space program employs over one million scientists and engineers, but there has been little substantial output. Risk taking is discouraged; thus, there has been only gradual development of simple systems and a lack of good instrumentation.

Sources: Anderson 1988; Budiansky 1987-88; Covault 1989a; DeAngelo and Borbely 1989; Lavoie 1985; "Soviet Technology," *Aviation Week* 3-20-89.

Access to space does not belong exclusively to national governments and their space agencies. Several private companies have developed space station concepts on their own, including Space Industries, Boeing, and Westinghouse, which are designing a $500 million Industrial Space Facility in Webster, Texas, for completion in the early 1990s, and General Electric, which is designing an unmanned, free-flying minilab.

The Japanese have been rather reticent to date regarding participation in the space industry; however, they initiated a $43 billion space development program for the period 1989-2006, which is composed of a series of commercial projects, including satellite programs, a robotic program, and a space factory for drugs and semiconductors, and infrastructural projects, including the construction of four platforms, an orbital maneuvering vehicle, and an inter-orbit transport space vehicle, as well as participation in the U.S. space station and construction of their own dedicated Japanese space station (by 2008). These projects are in addition to the HOPE spaceplane development project (see table 11). If all of these activities are realized, the Japanese will have a significant base from which to develop products and processes to meet the needs of the space industry as it grows, as well as to create new product concepts for Planet Earth consumers.

TABLE 11. *Japanese Space Commercialization Program, $43 Billion, 1989-2006*

Proposed project	Est. cost, billions of dollars	Timetable
Development of spaceplane "HOPE" (H-2 Orbiting Plane), with H-2 rocket booster	15.86	1989-2006
Participation in U.S. Space Station *Freedom* (space-processing module)	2.23	1987-1995
Polar-orbit platform	1.24	1988-2006
Station common orbiting platform	3.31	1989-2010*
Orbital maneuvering vehicle	0.82	1991-1995
Inter-orbit transport space vehicle	6.21	1992-2000
Geosynchronous orbit platform	2.48	1995-2008*
Manned platform	3.31	1996-2001
Dedicated Japanese station	7.31	2001-2008*
Satellite programs (+ H-2 booster) (incl. communications, broadcasting, weather)	20.5	1989-2004
Robotic space research program	2.4	Early 2000s*
"ADEOS" (Advanced Earth Observation Satellite) (precursor to participation in int. Mission to Planet Earth)	1.2	1994+
Space factory for drugs & semiconductors	No budget yet	Mid-2000s*

*Not included in the $43 billion commercial program.

Sources: Buell 1987; "Japanese Commission," *Aviation Week* 7-13-87.

Destination-Driven Innovation: The Evolution of Major Resource Development Projects

> . . . the empty fragility of even the noblest theorizings as compared with the definitive plenitude of the smallest fact grasped in its total, concrete reality.
> (de Chardin 1972, p. 62)

Colonizing the Moon or Mars seems almost frivolous when placed against the backdrop of problems, concerns, crises near at hand on Planet Earth. However, there are realities taking shape that may make such projects real lifesavers: Our planet is simply exploding with people; our supplies of raw materials and resources are being drained; continued pollution of the environment by manufacturing plants and the burning of fossil fuels is endangering the long-term sustainability of our ecosystem. And the relationships between atmosphere and climate uncovered in the examination of the greenhouse effect on Planet Earth, combined with further examination of existing conditions on Mars, might just reveal to us a methodology for terraforming Mars—delivering to us yet another entire planet to inhabit.

We have a knowledge base developed during the Apollo days that can be readily applied to a return mission to the Moon or to new ventures outward in the solar system to Mars. However, more than 20 years have passed since the landing of Apollo on the Moon, markedly diminishing the pool of experts with hands-on experience. We are fast approaching a point where it will become necessary to reinvent the wheel.

More than the expertise to be lost by not moving toward settlement of a particular destination is the expertise to be gained from the synergy required to plan, develop, and operate such a project. Solar scientists and electrical engineers, for example, tend to keep their own company in planning, designing, and prototyping solar energy systems and equipment. However, when the discussion changes to establishing a colony on the Moon, a whole range of very tangible problems and issues become immediately relevant: dealing with the long days and nights; providing energy for residential, commercial, and manufacturing support; providing sufficient backup to sustain life in the face of any and all calamities. Many insights will come from the interface of prospective corporate users, astronauts, scientists, and engineers.

Finally, the timing of such a magnificently difficult undertaking is critical. The vital capabilities must be in place before site development planning begins. It is simply not possible to begin to design an industrial city that includes technologies that are still being developed. All systems, processes, technologies used must have achieved closure: they must be fully developed, tested, and proven. It is simply not feasible to move workers out to construct a work camp with an unproven power source or oxygen supply. Thus, destination-focused innovation is subsequent to development of the vital technological capabilities, but the destination people can and certainly should have input into the capability development process.

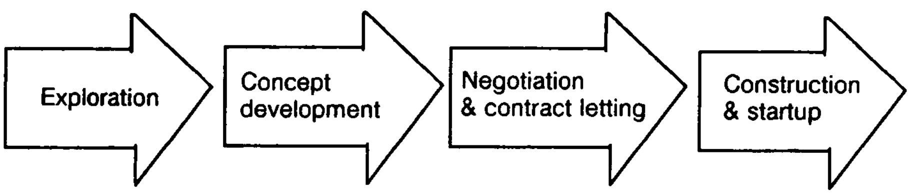
Once exploration of potential sites is completed, a destination is selected, and colonization has been decided on, the major resource development project begins to evolve (see table 12), following a very clear and well-tested path from concept development, through negotiation and contract letting, to construction and finally startup (see table 13), each of which will be examined in one of the following sections.

TABLE 12. *U.S. Mission Scenarios: Destination-Driven Innovation*

Destination	Proposed project(s)	Scope	Est. budget	Est. schedule
Moon (proposed)	As observatory	Sporadic missions to conduct scientific experiments; or unmanned astronomical observatory		
	As base colony (no Mars)	Live off the land, free of logistical support from Earth		
	As milestone to Mars	Manned lunar outpost: Multiple science operations Develop experience Staging area for Mars expedition	$33 billion /year	2019 on Mars
Mars (proposed)	Exploration Technologies R&D	Exploration, operations humans-in-space vehicle technology research to get to Mars at a reasonable cost		
	Mars Rover Sample Return (MRSR)	10 unmanned precursor sampling missions to photograph, return rock & soil samples, meteorological data, water content, mineral composition of soil	$40 billion	10 years
	Mars via Moon	(see Moon)		
	Mars direct	Single expedition	$36 billion /year (peak)	2019
		Manned outpost/ no lunar base		
		Manned outpost prior to lunar base		
	Phobos & Deimos	Moons of Mars		
Universe (under way)	35 missions planned	Extraordinary cosmological discoveries expected that could revolutionize major areas of science, especially physics (unmanned)	$18 billion	1990-95

Sources: Broad 1989, 1990a, b, d; Cook 1989; Covault 1988, 1989b, c, d; Del Guidice 1989; Lane 1989; "Mars, the Morning After," *Christian Science Monitor* 7-27-89.

TABLE 13. *Life Cycle of a Major Resource Development Project*



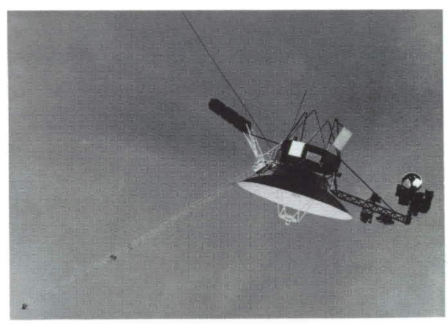
Development of a particular destination in space is not free from the need to innovate and advance. We have no experience in establishing large communities that are completely dependent on their infrastructure for oxygen. We have not yet developed construction techniques for connecting materials that will endure in space and provide sufficient protection against radiation. Our entire body of materials, construction techniques, logistical concerns, and supply networks must be experimented with and established. Our notions of project management must be revised—perhaps even to include "breakthrough" management—so that, as the project unfolds, innovative solutions can be sighted, experimented with, and efficiently integrated.

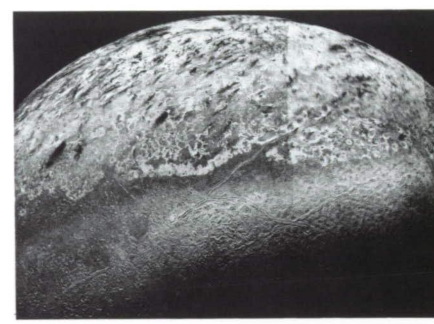
We are not completely in the dark in this regard. All of the very largest scale development projects installed on Earth have had some ground-breaking technology component. In most cases the technology already existed and just needed to be adapted to the expanded scale. Many, however, introduced completely new technology. We may have already zeroed in on the two or three best materials for use in space, but it is another issue altogether to produce enough and work with it in the amounts required to establish an industrial city.

Exploring Uncharted Courses

Before we can reach out to space, master the abundance of its resources, and make it truly ours, we must understand what is there, how it is laid out, and how the various components interact. This requires developing and operating instruments to measure, define, bring back samples, map, photograph, and provide high-resolution imaging.

Unmanned planetary probes have proven to be efficient, exciting, and scientifically rewarding. Voyager 2, for example, was launched 12 years ago and is still functioning flawlessly. In fact, we are the only spacefaring nation that has had the confidence and ability to send machines on long, intricate journeys to the giant outer planets (see fig. 9). This is an exclusive strategic niche in which we have faced little competition to date—perhaps because the payback from such activities is not immediately apparent.





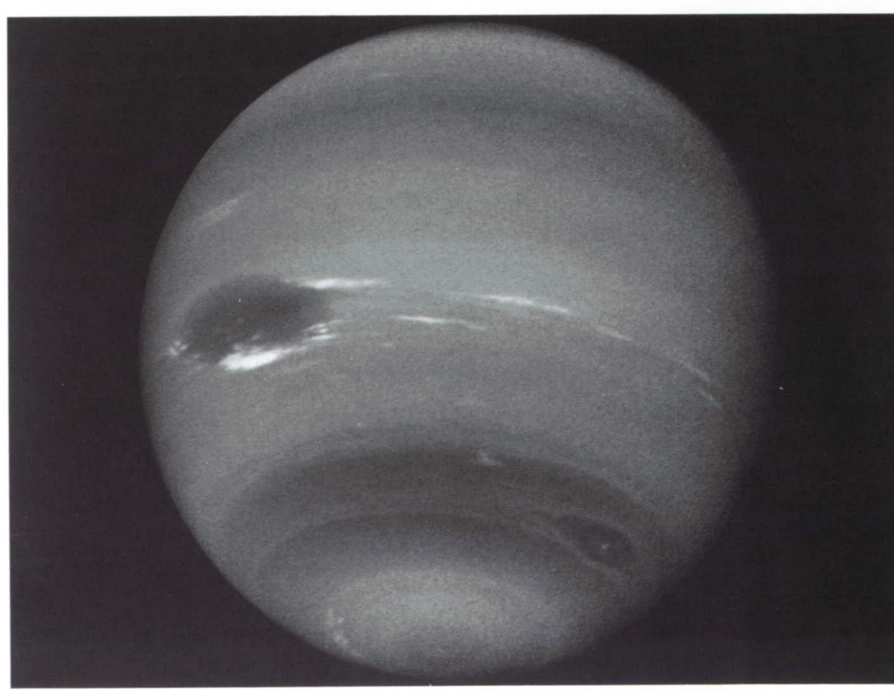


Figure 9

Voyager at Neptune

This Voyager 2 picture of Neptune, taken in August 1989, is one of the best full-disk views of that planet. Neptune, 30 000 miles in diameter, is the smallest of the big gaseous outer planets. The small white features are high clouds of condensed methane, which cast shadows on the top of the denser atmosphere below. The two larger, dark features are the Great Dark Spot and Small Dark Spot. They are the upper expression of giant storms in the atmosphere of Neptune and appear to be similar to the Giant Red Spot on Jupiter.

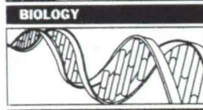
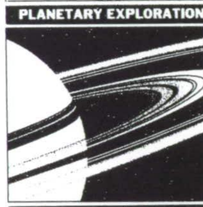
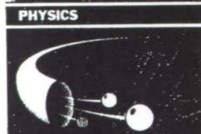
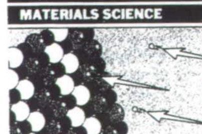
This view of Triton is a mosaic of a number of close-up photographs taken on August 25, 1989, during the closest encounter of Voyager 2 with the satellite of Neptune. Triton has a complex surface, with a few craters, probably made by comets. Triton probably has a silicate core about 1250 miles in diameter covered by a crust of water ice about 200 miles thick. A thin layer of nitrogen ice may overlay part or all of the water ice. Some of the complex morphology is caused by the fracturing of these icy mantles and the outflowing of liquid water at some time in the past. The temperature at the surface of Triton was measured by Voyager 2 at 38 K, making it one of the coldest surfaces in the solar system. Methane frost is also likely present, and the reddish color of some regions may be caused by sunlight uv radiation reacting with the frozen methane.

A balanced approach is a basic tenet of NASA's current space science strategic plan, which includes a mix of moderate and major missions totaling six launches a year in the early 1990s (Smith 1989). A major new science mission is planned every year through the turn of the century. Over the next 5 years, the United States has a firm schedule to put up 35 scientific flights, a rate 6 times as great as during the past decade and equal to that of the 1960s (Cook 1989).

The task of developing an instrument with which to explore the universe is getting to be a highly collaborative effort. "Big science"—a term coined by Alvin Weinberg in the 1960s when he was director of the Oak Ridge National Laboratory in Tennessee—involves the collaboration of teams of researchers, technicians, Government officials, university administrators, and industrial contractors and large sums of money to produce new instruments to advance our understanding of nature (Lederman 1990) (see table 14, which accompanied a New York *Times* article on the Hubble Space Telescope). The Hubble Space Telescope, the most expensive unmanned scientific spacecraft ever built by the United States and the most difficult to operate, was developed by 60 scientists from 38 institutions selected by NASA and involved nearly every sector of the space agency. A $1.5 billion effort, with an operating budget of $200 million/year, it is a product of such U.S. organizations as the Jet Propulsion Laboratory, which developed the wide-field camera; Lockheed Missiles and Space Company, which built the spacecraft; and Perkin-Elmer Corporation, which devised the electro-optical system. Critical help was also provided by the 13-nation European Space Agency, which provided 15 percent of the funds and supplied some of the equipment in return for an equivalent amount of observing time by its scientists (see table 15) (Wilford 1990a, b).

TABLE 14. *The High Price of Future Scientific Progress*

Federal science projects to be carried out in the 1990's whose construction costs are $100 million or more:

Category	Project	Expected Completion	Life	Cost To Build
SPACE SCIENCE				
	**Space Station** An orbiting outpost from which astronauts are to conduct a variety of scientific experiments and possibly set up a forward base for the manned exploration of the Moon and Mars.	1999	30 years	**$30 billion**
BIOLOGY				
	**Human Genome Project** The largest basic biology project ever undertaken, seeking to delineate the entire human genetic code, consisting of three billion subunits of DNA that influence human development.	2005	--	**$3 billion**
PLANETARY EXPLORATION				
	**Cassini Saturn Probe** Unmanned craft to examine the giant planet's atmosphere, rings and moons	1996	12 years	**$800 million**
	Comet Rendezvous and Asteroid Flyby Unmanned craft to rendezvous with comet Kopff for three years of study	1995	12 years	**$800 million**
	Mars Observer Unmanned craft to orbit planet for observation of surface, atmosphere and gravitational fields	1992	3 years	**$500 million**
EARTH OBSERVATION				
	**Earth Observation System** Orbiting satellites to obtain wide array of data on environmental changes	2000	15 years	**$17 billion**
	Upper Atmosphere Research Satellite Satellite to gather data on earth's ozone loss and other chemical trends	1991	3 years	**$740 million**
	Ocean Topography Experiment Satellite to map ocean circulation and its interaction with atmosphere	1992	3 years	**$480 million**
ASTROPHYSICS/ASTRONOMY				
	**Advanced X-Ray Astrophysics Laboratory** Satellite to investigate black holes, dark matter, age of universe	1997	15 years	**$1.6 billion**
	Extreme Ultraviolet Explorer Satellite to map sky in unusual region of electromagnetic spectrum	1991	2.5 years	**$200 million**
	Gravitational Wave Observatory Two ground-based instruments to try to detect gravity waves	1995	20 years	**$190 million**
	8-Meter Optical Telescopes Two ground-based instruments for general study of stars and planets	2000	30 years	**$170 million**
PHYSICS				
	**Superconducting Supercollider** 54-mile instrument to study elementary particles and forces	1999	30 years	**$8 billion**
	Relativistic Heavy Ion Collider 2.5-mile atom smasher to probe structure of atomic nucleus	1997	20 years	**$400 million**
	Continuous Electron Beam Accelerator 1-mile instrument to probe same structure in different way	1994	20 years	**$265 million**
MATERIALS SCIENCE				
	**Advanced Photon Source** Light-generating ring to probe matter's structure	1997	30 years	**$455 million**
	High Magnetic Field Laboratory Facility for study of magnetic phenomena and materials	1995	30 years	**$110 million**
	Advanced Light Source Small light-generating ring to study atomic structure of matter	1993	20 years	**$100 million**
TOTAL				**$64.8 BILLION**

Taken from William J. Broad, 1990d, "Heavy Costs of Major Projects Pose a Threat to Basic Science," New York *Times*, May 27, sec. A, pp. 1, 20. The *Times'* sources: NASA, Department of Energy, National Science Foundation. Illustrations by Seth Feaster.

TABLE 15. *The Hubble Space Telescope*

Vision:	Revolutionize mankind's understanding of the universe
Mission:	Determine • How fast the universe is expanding • How old the universe is • What the fate of the universe is
Scope:	Focus on visible and ultraviolet light from all classes of heavenly bodies
Sponsors:	Johns Hopkins University Space Telescope Science Institute NASA
Operation:	Association of Universities for Research in Astronomy, a consortium of 20 institutions
Design/ development:	60 scientists from 38 institutions (selected by NASA)
Equipment development:	• Wide-field camera—Jet Propulsion Laboratory • Faint-object camera—European Space Agency • Spacecraft—Lockheed Missiles and Space Co. • Electro-optical system—Perkin-Elmer Corp. • Glass plates—Corning Glass Works
Development budget:	$1.5 billion, with a final cost of $2.1 billion including $600 million in ground support facilities to test and operate the telescope and process data from it
Operational budget:	$200 million/year
Maintenance:	Serviced by Shuttle astronauts every 2 years; returned to Earth every 5 years for a complete overhaul
Planned observations:	1500 astronomers in 30 countries submitted a total of 600 proposals for observations, in five categories: • Planets in the solar system and search for planetary systems around other stars • Stars and stellar systems • Areas between stars • Galaxies • Quasars

Source: Wilford 1990b.

Projects such as the proposed Exploration Technologies (formerly Pathfinder) R&D to develop exploration, operations, and piloted space vehicle technology to get to Mars at a reasonable cost and the Mars Rover Sample Return (MRSR), a set of 10 unmanned precursor sampling missions to photograph, return rock and soil samples, and gather meteorological data in order to determine the water and mineral content of the soil (fig. 10) are just some of the exploratory support systems essential to determining whether a particular destination is worth developing.

The two major destinations under serious discussion are Mars (6 to 12 months away) and the Moon (3 days away). Many questions must be answered before a development location is targeted and detailed planning can begin.

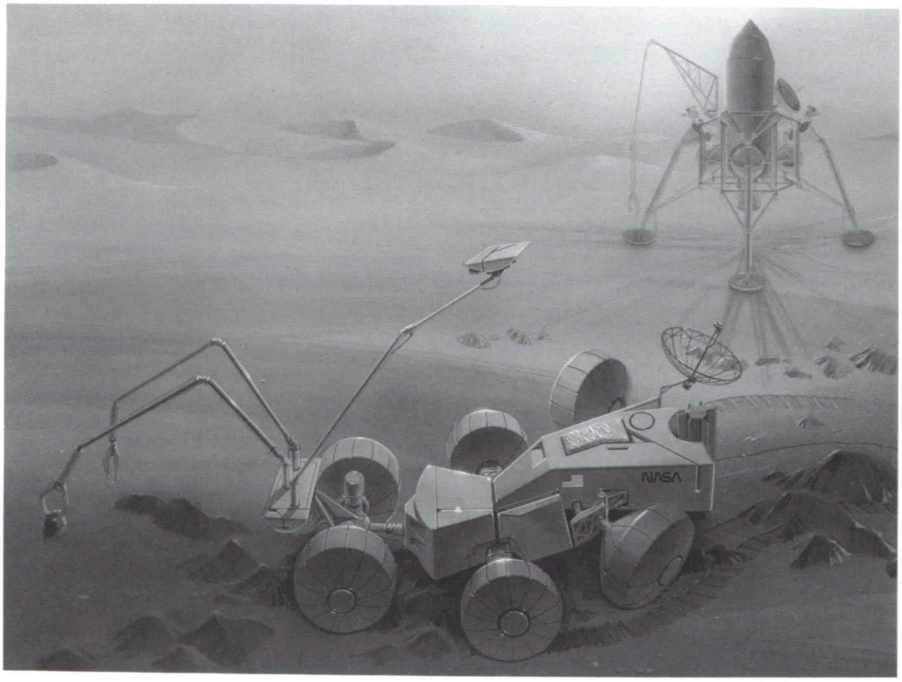


Figure 10

Mars Rover Sample Return

Robotic collection and return to Earth of martian geologic samples would greatly increase our understanding of the history of Mars and would help us make workable plans for human exploration of Mars. Analysis of the samples would help establish how recently volcanoes have been active, what might have happened to an earlier, more Earth-like atmosphere, and whether surface conditions were ever hospitable to living organisms. In addition to high scientific value in its own right, such knowledge would enable astronaut crews to focus on the most important locations and scientific issues during their later exploration of the Mars surface.

Sample return in advance of human explorers would require either autonomous or remotely operated vehicles that could collect and package samples of rocks, soil, and atmosphere and launch them from the Mars surface to Mars orbit and on to Earth. A roving vehicle (foreground) is one attractive option for collecting the desired samples. Whether the rover moves on wheels (as shown), tracks, or legs, it will have to navigate around surface hazards and deliver the samples to the stationary launch vehicle (background). Current planning suggests that each such rover/launcher combination would be capable of returning about 5 kilograms (11 pounds) of samples to Earth.

Artist: John Frassanito

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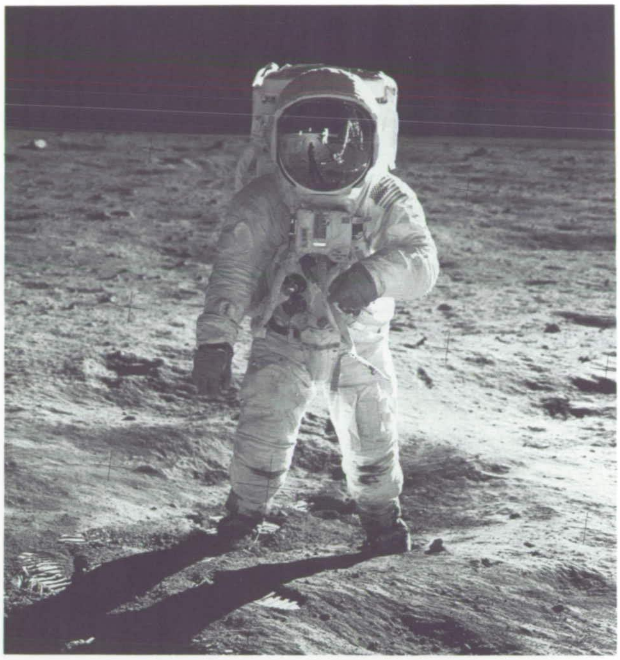
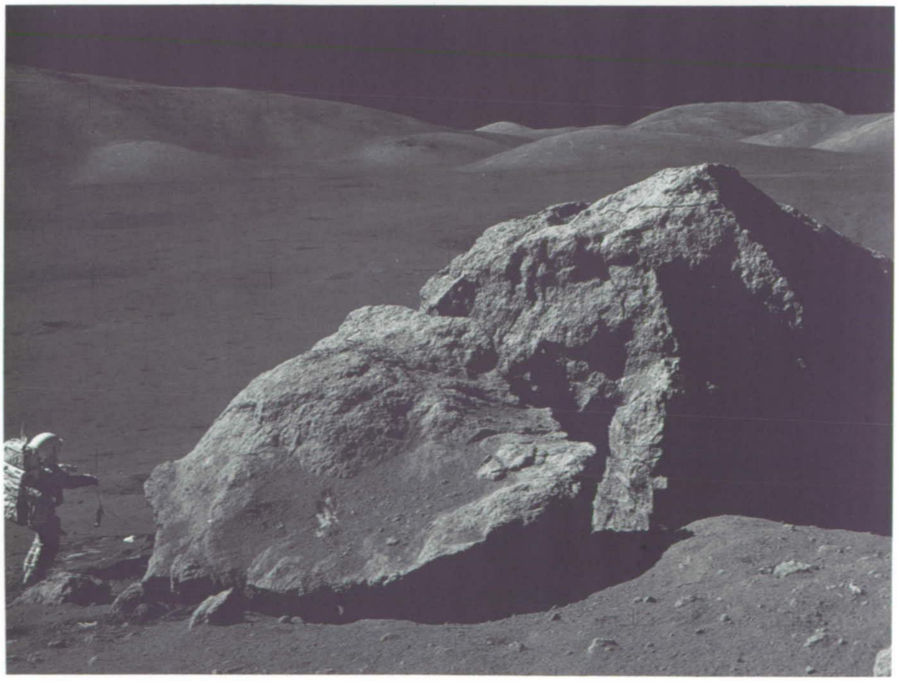




Men on the Moon – the First and Last (So Far)

Both Apollo 11 moonwalkers can be seen in the photo above: Edwin "Buzz" Aldrin is the subject of photographer Neil Armstrong, who can be seen reflected in Aldrin's visor. Apollo 17 photographer Gene Cernan was not so lucky when he snapped the photo below; his subject, geologist Harrison "Jack" Schmitt, was concentrating on taking a sample of "House Rock."

The following is one of a series of 5-minute radio programs. Entitled The Engines of Our Ingenuity, *the series is written by mechanical engineer John H. Lienhard and presented by the University of Houston's College of Engineering.*

Mining the Moon

For 20 years, I've wondered why we lost interest in the Moon so quickly after we first walked on it. Maybe it was because we looked over the astronauts' shoulders and saw only a great slag heap. Now geologist Donald Burt asks if it's only that or more. Does the Moon hold riches, or is it just a scabrous wasteland?*

We know a lot about the Moon today. It's rich in aluminum, calcium, iron, titanium, and magnesium. There's also plenty of oxygen on the Moon, but it's all bound up in compounds that are hard to break down. You can get at it, but it'll take a lot of processing. Maybe we can pull some hydrogen and helium-3 out of the rocks as well.

What's absolutely missing on the Moon is anything volatile. There's no water—no loose gas or liquid of any kind. The vacuum on the Moon is more perfect than any we've ever created on Earth.

So can we go after minerals on the Moon? Before we do, let's think about mining and smelting on Earth. We use huge amounts of water—huge amounts of power. We consume oxygen and we put out great clouds of gas. But there is no water on the Moon, nothing to burn, and no power until we put it there.

Without water, the Moon hasn't been shaped the way Earth has, with alluvial strata and deposits. Many of its riches are all mixed together in the surface

(continued)

*Donald M. Burt, 1989, *Mining the Moon,* American Scientist, *Nov.-Dec., pp. 574-579.*

For Mars, we need to know: Is there any way to add significant oxygen to the atmosphere and make the planet livable? Was there ever life there? Was there running water? How can the severe temperatures be withstood? Are the moons of Mars similar to our planet's Moon, or different?

For the Moon, we need to know: Does water exist at the poles? Can we manufacture it from lunar resources? What kind of shelter is required to protect against radiation? Should we walk away from development as it is just a heap of stones, or would use of such techniques as a glass enclosure (Biosphere II) allow the re-creation of Earth's atmosphere?

As exploration passes from just a cursory look to indepth analysis of resources available and assessment of feasibility and costs to exploit, the risks and stakes become higher and the need to share risks becomes essential. NASA's role here should be to develop the approaches and techniques for getting to the resource bases and to develop the instruments to measure ore quality. Having done so, the agency should attract resource development companies or entrepreneurs to assume the responsibilities of more detailed risk assessment, extraction, and development.

Developing the Project Concept

Assuming that a location has been identified which provides sufficient resources to reduce or eliminate dependence on supplies from Planet Earth and does not appear to be life-threatening, the next step is to scope out a project concept. This is a critical event requiring enormous thought, as the format decided on can prepare the way for effective cooperation and resourcefulness, or it can establish an arena of intensive competition and friction.

Lunar or martian communities could be company-owned towns (like mining towns in Australia), country-owned towns (similar to the early settlements in the United States), or possibly international towns, the heart of which would be an internationally consistent infrastructure provided by a consortium of participating national space agencies to foster and facilitate residency and participation by entrepreneurs, transient workers, and a full melting pot of Earthlings of all races, nationalities, and backgrounds.

The critical decisions pertain to allocating ownership and project management responsibility among the industrial and infrastructure components of the development project under each scenario.

The company-owned spacetown: A large resource development company (such as an oil extraction and hydrocarbon processing, a metal mining and processing, or a pulp and paper company on Earth) usually decides to set up camp in a remote location because there are resources to be extracted and processed and there is a clear profit advantage to assuming the risks associated with life in a forbidding environment. If the location is far from civilization, the resource development company takes responsibility not just to supply the tools, techniques, processes, and people to perform the profit-generating task but also to provide the life support components usually supplied by governmental agencies in more civilized areas—such as water, food, electricity, transportation vehicles and networks, education, and health care.

From our experience with company towns on Earth, it is clear that they are homogeneous (even if the project sponsors are joint-venture partners—everyone is working in the same place). Problems faced by resource developers responsible for establishing a company town are monumental, encompassing issues far beyond business management and profit generation. Besides the logistical problems common to all such mega-scale undertakings, there is the problem of transplanting a complete communal system. The isolation, the feelings of hardship, and the social conflicts of workers operating under such stressful conditions add dimensions to the management task that are perhaps the most complex. It appears that technologically we are capable of bringing enormous resources to bear on a problem. Risks and exposure can be reduced to tolerable levels via joint ventures and multicompany consortia. We have expertise in managing in remote locations and marshaling the very best talent for a particular task. The real block to smooth performance has proven to be the human element. Planners frequently overlook the environmental, social, and political issues involved in creating a company town here on Earth—an oversight which may, in fact, account for the most costly budget overruns and schedule delays.

It should be noted that the cost of these large infrastructure components raises the break-even point of the project, thereby requiring that the productive output be raised. Infrastructure development also increases project complexity, as responsibilities that usually belong to local governments fall to the project sponsors. And the more complex the project, the more difficult and dangerous the management and coordination task.

***Mining the Moon** (concluded)*

layer of dust. We'll probably begin by surface mining for oxygen to sustain our outposts in space. Metals will be useful byproducts.

Pollution would be a terrible problem if we mined the Moon the way we do Earth. The Moon's near-perfect vacuum is going to be useful in all kinds of processing. If we dumped gases on the Moon, the way we do on Earth, we'd ruin that perfection.

You see, most gas molecules move more slowly than the lunar escape velocity. Only the fastest ones get away. Now and then, slower ones are sped up as they collide with each other. Then they also can escape. Over the years, the Moon loses any gas released on its surface, but not right away. So we have to invent completely closed processes to take the Moon's wealth. That way we'll protect one of the Moon's greatest resources—its perfect vacuum.

The Moon is a rich place, but we must put our minds in a wholly different space to claim its riches. The Moon will reclaim our interest as we learn to see more than a slag heap. The Moon has held our imagination for millennia, but in a different way each time our knowledge of it has changed. Today, our vision of the Moon is on the threshold of changing yet again—as we learn to look at it with a process engineer's eyes.

The country-owned spacetown: We could go to the Moon or Mars, plant our flag, and plot out our territory (though we cannot *claim* the territory; see Goldman's paper on international law) much as the early settlers did in America in the 1600s. We would create a rapport within the town but might recreate the conflict and friction between towns owned by different countries which has occurred on Earth.

The governmental body, possibly NASA, would have an important role to play: There are certain facilities which are funded, installed, and managed by governmental authorities in communities around the world; these include power, transportation systems, water and waste treatment systems, and medical, educational, athletic, and other such facilities that promote the general well-being of the population. The scope of space infrastructure will certainly be larger than the King Abdulaziz International Airport in Saudi Arabia (fig. 11), the largest airport in the world, which was built in the middle of the desert at a cost of $4.5 billion by 10 000 workers (at the peak of construction). It is a self-contained city that includes a desalination plant to get drinking water out of sea water, a hospital, and its own telephone system. It was constructed to provide adequate shelter, eating facilities, and restroom accommodations for 80 000 travelers expected during the 36-hour period of the hajj, the annual Muslim pilgrimage to Mecca.

Figure 11

South Terminal of the King Abdulaziz International Airport in Saudi Arabia

Courtesy of the Information Office of the Royal Embassy of Saudi Arabia

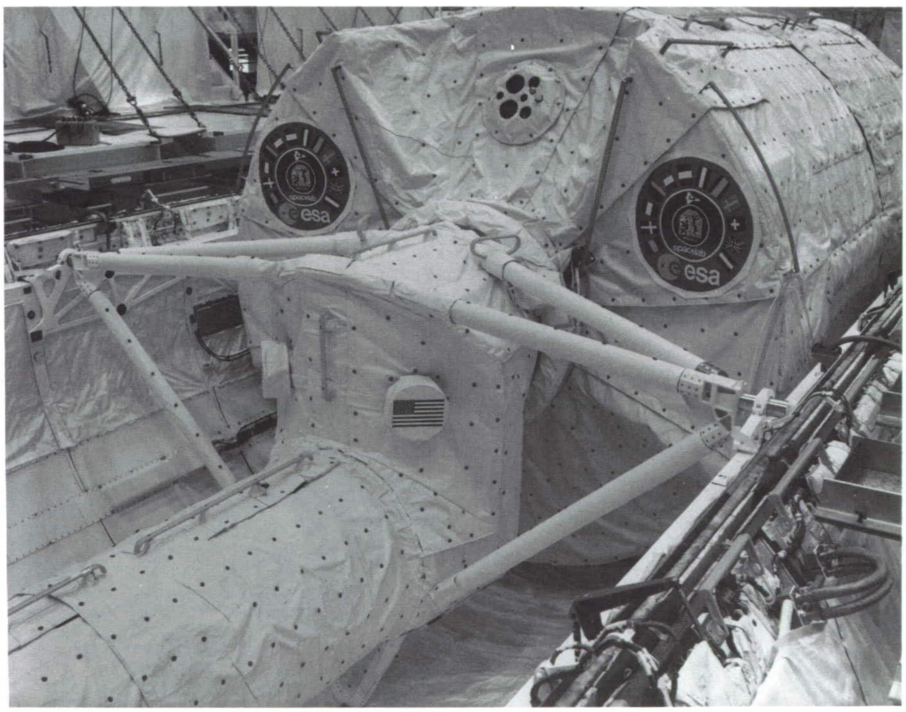
The advantage of governmental development and management of supporting infrastructure is that it provides access to life-sustaining facilities to small as well as large enterprises and to individuals of all economic levels, enabling them to undertake entrepreneurial as well as corporate economic activities.

Governmental involvement in these sectors encourages the most broad-based development scenario. Since these projects do not necessarily generate a profit, the go/no-go decision is typically based on cost/benefit analysis: How many people will be serviced by a particular infrastructure facility and how much economic activity can be stimulated in return for the costs assumed? Government initiation is not intended to create a welfare state but rather to foster economic activity, support diversified growth, and above all create taxpayers who will pay off the debt incurred in establishing the infrastructure, cover its operating costs, and support infrastructure expansion. NASA could seed the growth of the initial community and then sell the infrastructure to the community, once a sufficient economic base was created.

The international spacetown: The opportunity exists to go beyond community development as we know it today and establish a true international—or citizen of Planet Earth—community. A consortium of national space agencies could jointly plan, design, and install an infrastructure network to support a broad diversity of economic activity in space. Technical, financial, and market supply and demand benefits could be derived from this global cooperative effort. It is essential that technological compatibility and interchangeability be achieved so that products and processes will be transferable to and usable by all. Standards for gravity, oxygen, food quality, screw sizes, shielding densities, and maintenance requirements need to be set. Space medical standards and practices must be established. The costs of setting up life in such remote locations will be enormous. It will be wise to share fully the costs of infrastructure development, undertaken in cooperation. Again, the goal is to create a community of economically productive taxpayers, who will begin to reimburse the national space agencies for their design and development efforts (funds which could then be used to move to a subsequent planet and begin the same seeding process).

The ultimate objective of the international spacetown, however, is to create a thriving self-governing metropolis that is democratic and full of opportunity for individual entrepreneurs as well as large, established global corporations.

In an environment where there probably will not be curtains at the windows and paintings on the walls for some time, it is important that individual creativity and ingenuity be highly respected and given broad leeway to realize itself.



Spacelab 1, an Example of International Development of Space Infrastructure

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Negotiating Risk Allocation

At the very largest, megaproject scale of development, no single organization has yet been able to finance, provide the technology for, or market the output of the completed facilities alone. A broad array of technologies, both infrastructural and industrial, are required in large volumes to attain mega-scale project parameters. In addition, abundant transfers of proven technological processes and secured market demand for the output are required to attain economic feasibility. The project requirements define the extent and nature of the inter-organizational collaborations needed to bring the project to fruition. See table 16.

TABLE 16. *Project Requirements and Consortia Formation*

		Requirements and consortia contract types		
Type of project	Project requirements	Capital sourcing	Technology transfer	Market access
Resource development project	Technology transfer Capital sourcing Market access	High risk	Custom-tailored	Critical to economic viability
		• Equity • Loan and repayment in output • Suppliers' credits	• Construction management • Design/construct • Consortium of contractors	• Buyers' consortium • Production sharing • Long-term purchase agreements • Coproduction (or barter or payment in kind)
Turnkey manufacturing facility	TT CS MA	Low risk	Off-the-shelf	Not critical
		• Suppliers' credits tied to turnkey contract • Possibly some equity, but not necessary	• Turnkey contract • Turnkey contractor's consortium	
Infrastructure development project	TT CS	Low-high risk (depending on type)	Generally custom-tailored	Cost/benefit calculation
		• Concessionary financing • Equity usually held by governmental ministries	• Construction management • Design/construct • Consortium of contractors	

Commercial resource development projects are undertaken because of a clearly visible opportunity to make a profit in the face of clearly high risks. The extraction and processing of fuels and minerals, and in certain cases the harnessing of power sources, come under this heading. In the developing world, these projects are usually sponsored by publicly owned corporations or state-owned enterprises and depend on private equity capital in addition to any public loans or grants the project might be eligible for. Overruns and delays during project implementation can as frequently be attributed to the partners selected (too many, in conflict, different goals for the project) as to logistical and other difficulties intrinsic to the project itself.

Some commercial projects are "turnkey" projects, in which a factory can literally be transplanted to the site. These might be manufacturing facilities, hydroponic food farms, and other types of processing plants that are self-contained—perhaps even a factory to extract liquid oxygen from regolith on the Moon (fig. 12). Turnkey projects are lower risk and are typically supported by export financing from the home country of the technology process owner, in addition to equity capital provided by the plant owners.

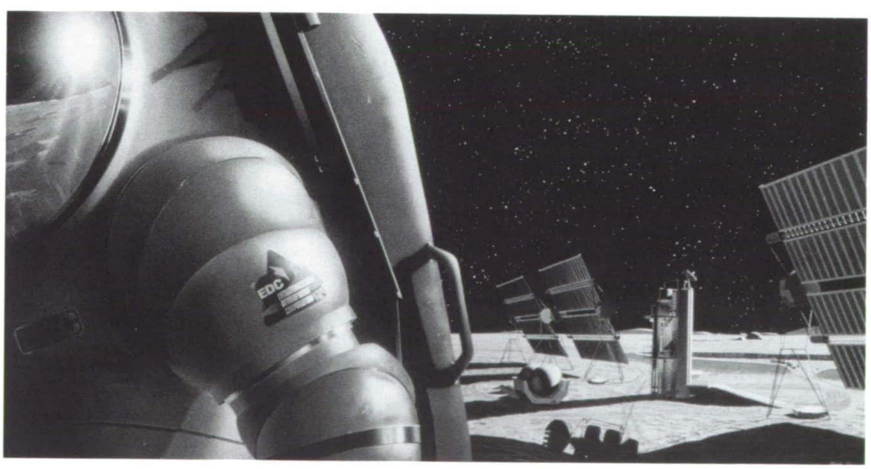


Figure 12

A Turnkey Factory on the Moon

Development of lunar resources may turn out to be a commercial enterprise. In this artist's illustration, a fictitious company, the Extraterrestrial Development Corporation (EDC), has installed an oxygen plant on the lunar surface and is operating it and selling the oxygen produced to NASA and possibly other customers. The fluidized bed reactor in the background uses ilmenite concentrated from lunar soil as feedstock. Oxygen is extracted from this ilmenite by hot hydrogen gas, making water vapor. The water is electrolyzed, the oxygen is captured and stored as a cryogenic liquid, and the hydrogen is recycled back into the reactor. The power for the plant comes from the large solar collectors on either side of the reactor.

Artist: Mark Dowman

The final class of projects is infrastructure development projects, which provide life-sustaining needs to a community, enabling its members to carry out productive, wealth-generating activities. Such a project is often owned and operated by a governmental agency and, once operational, supported by taxes and user fees. The initial installation of these infrastructural facilities, such as water supply, waste treatment, power supply, public housing, sports and recreational facilities, as well as transportation and communication networks and public administration buildings, is typically financed by loans provided by international development agencies or capital raised from the public in the form of bonds. A core infrastructural network can be established at the start of human settlement on other planets and expanded as the human base it supports is extended.

In my experience of megaprojects developed on Planet Earth, in particular in remote locations in developing countries (Murphy 1983), I have seen effective multicompany efforts to stabilize the project parameters through consortia negotiation and inter-organizational contracting.

What a consortium is: In general, as the level of risk increases, so does the likelihood that a consortium of companies will be formed to insulate any one participant from potentially devastating financial consequences, should the project fail. I am consciously substituting the term "consortium" for the expression "joint venture," because it suggests a more pragmatic basis for collaboration and for sharing risks, negotiating responsibilities, and determining the split of profits, if the project succeeds. The parties involved in a consortium contract among themselves to specify the responsibilities of each. The common features of a consortium are that

- It is task-based. Participants are selected on the basis of which project requirements (capital sourcing, technology transfer, or market access) they are capable of satisfying, rather than on who they are or how large their organization is.

- It involves risk-sharing. All members assume some measure of risk. Each member's reward is tied to the level of risk assumed, with the payback period being clearly delimited.

- There is some competitive advantage. Typically, a member is selected because it can offer to the combination of participants one or more competitive advantages.

The decision to form a resource consortium appears to be more related to the level of project risk than to the level of sophistication of the capabilities of the players involved, as these collaborative arrangements can be found throughout the developing world in all industry sectors and have involved most of the leading organizations of the world.

How project needs are met: These collaborative undertakings provide an effective way to satisfy the enormous capital sourcing, technology transfer, and market access requirements common to all megaprojects by ensuring that the critical drivers of economic viability are satisfied. However, the contributions of such consortia to enhanced effectiveness may vary by industry sector:

- For metal mining projects, consortia make it possible to increase the scale of a project beyond the financial abilities of a single company in order to cover infrastructure development costs (sometimes up to 60 percent of total investment) and meet economic criteria. These requirements have been more intense of late, as most of the Earth's remaining metal reserves are in relatively inaccessible locations.
- For metal and petrochemical processing projects, consortia enable companies to eliminate the threat of price fluctuations on the output by establishing long-term purchase agreements with buyers, while at the same time hedging their risks over several projects by taking a low equity share in each.
- For liquefied natural gas (LNG) projects, consortia are formed to establish a long-term purchase agreement with a guaranteed buyer who must also build a tailormade receiving terminal to unload the output. Unless this crucial requirement is met, the construction of the production facility—typically ranging from 500 million to several billion dollars—cannot be justified.
- Oil refineries, by comparison, seem to have little problem in finding buyers for their products; thus, the need to form a consortium to build one has been less common.

Not only does the resource consortium provide an important vehicle for controlling some of the external risks of a project which are beyond the sponsor's ability to manage alone, but also, depending on the expertise of the partners, the consortium may bring together sponsors whose technology and managerial assistance can enhance control of the internal risk factors of the megaproject at the same time. On the other hand, if managerial expertise is lacking, contracts for project or construction management can be established with organizations skilled in the weak areas.

How participant risks are minimized: Capital funding and market access are often secured for the project through multi-organization consortia, involving a share of the project equity while minimizing risk exposure for the respective participants:

- A multinational resource development consortium is typically composed of shareholder corporations from many countries, each holding a very low percentage of equity, combined with long-term purchase agreements for access to the raw materials output by the project. By taking a low equity interest in the project, each corporation is able to syndicate its investment risks over a large number of projects and thereby stabilize its raw material supplies.

- A national resource development consortium is composed entirely of companies from the same country; it is composed of all companies in a particular industry at a very low equity share per company, with a substantial portion of the capital loaned to the project by agencies of their government. The net effect of such a consortium is to equalize the risks and stabilize supply sources, as well as the cost of those raw materials, across an entire industry within a country. Thus, a country like Japan, which depends on imports for 90 percent of its raw materials, can marshal industry-wide support for any raw material acquisition the national government would like to make. Furthermore, it shifts competition between companies from obtaining the best price for raw materials to such downstream advantages as more efficient processing or manufacturing facilities and more focused marketing or distribution networks.

It is becoming easier to put together consortia, as the key players have built up an experience base with respect to inter-organizational collaboration. As industries have evolved over the last two decades, the ground rules for collaboration among international developers have changed from nationalistic to global strategic perspectives and dimensions. Joint technology and marketing ventures among companies that have traditionally been competitors have become common.

Managing Project Construction and Startup

As complex as construction and startup are in the most remote of locations on Earth, they will be orders of magnitude more complex on another planet. If handtools or screws are forgotten, it will be a long way back to get them; replacement parts will not be an airplane ride away; and Federal Express or UPS will probably not have offices in the closest city.

Several decisions can affect how roughly or smoothly the construction and startup will go.

Integrated or phased: Megaprojects, whether resource or infrastructure development, are brought to fruition under management scenarios that best meet the needs of the participants, the capital constraints, the level of technology in hand, and the demand for the output. Projects can be developed in an integrated manner, installing all components at the same time. An example is the $20 billion Al Jubail Industrial Complex in Saudi Arabia (fig. 13). Expected to take 20 years

Figure13

Seaport of Al Jubail Industrial Complex in Saudi Arabia

Courtesy of the Information Office of the Royal Embassy of Saudi Arabia to develop, with a completion date set for 1997, it includes three petrochemical plants, an oil refinery, steel and aluminum plants, water and waste treatment facilities, a desalination plant, housing, a training center, a seaport, and an international airport—all of which were planned and developed under one, integrated project concept.

Projects can also be developed in a phased manner. One facility can be installed which then provides the base from which additional facilities can be built. An example is the development of the Bintula area in Malaysia. First a $5 billion liquid natural gas facility was installed, supported by a basic work camp and infrastructure. A subsequent project is being planned to develop the entire area as a resort, including a new city, at a cost of $10-15 billion.

Each approach has benefits and risks, which are summarized in table 17. An integrated approach puts stress on the internal aspects of the project, making procurement, logistics, and labor management more complex. However, there are external advantages to coming onstream earlier, such as a shorter period for borrowing capital and a quicker payback.

Phased development stretches out the completion date of the fully integrated project, thus allowing competitive inroads, but permits greater control over each section. Procurement is phased, there are fewer players involved at one time, and adjustments are smoother.

TABLE 17. *Economics and Project Sequencing*

Approach	Risks	Benefits
Integrated development	Overload (internal) • More complex • More procurement, logistics problems • Labor management • Cultural conflicts	Online sooner (external) • Shorter demand for capital • Quicker return
Phased development	Competitive threats/ inroads (external) • Competitive moves • Inflation in cost • Other variances in demand estimates	Able to test out one step before moving on to another (internal) • Simpler • Phased procurement • Fewer players at one time • Smoother adjustments and interface

For NASA, the issue is whether it is better to develop a work camp on the Moon only, or on the Moon and on Mars, or on the Moon first and then on Mars. Should a small outpost be developed, or an entire community? What functions will the base serve? Is it an observation post from which to conduct science, or is it a resource development base for mineral extraction, or is it an infrastructure base from which to explore and experiment in search of wealth-generating activities? The ability to answer these questions will be determined by the findings from various exploratory missions. The ability to respond to those findings will depend on the extent of technological breakthrough achieved in our capabilities.

Achieving synergy: The most important opportunity for capitalizing on cost-reduction opportunities, not to mention actively preventing overruns, lies in maximizing efficiencies during the construction phase; that is, the period during which most of the capital is spent. The ability to recognize and take immediate advantage of the tradeoffs that must be made daily can provide significant cost savings. Megaprojects often entail several kinds of construction by multiple contractors simultaneously; therefore managerial synergy is critical: (1) from one stage to another, (2) among processes installed, and (3) between the goals of the sponsors and the services of the technology providers. Attention must be paid as much to the transition points of a megaproject as to performance within each component. Unbudgeted costs have often been incurred at these critical transition points, where leadership responsibility has not been clearly defined.

Unique megaproject management expertise: Companies which have been successful providers of project management expertise in the developing world have relied on their strong reputations and expertise from their home countries as their entree into the megaproject arena. Since companies are not awarded contracts to experiment with or diversify their services but rather to deliver proven expertise, U.S. firms have been the companies of choice because of their track record of fully implemented mega-scale projects that have been developed at home. All projects of $1 billion or more in the developing world requiring project management capabilities (such as oil refineries, gas processing facilities, and transportation infrastructure) have been awarded exclusively to U.S. design/construction firms.

The most complex megaprojects have been designed, engineered, constructed, and managed by the U.S. design/constructors Bechtel, Fluor, and Ralph M. Parsons. These three companies are superior in their ability to deal with complexity through sophisticated project management systems and worldwide procurement networks. This suggests that NASA's continued attention to megaproject management innovation will ensure that this U.S. tradition of being the preeminent providers of complex project management services worldwide—a critical national competitive advantage—will be sustained.

The consortium is also a common approach used by small or medium-sized design, engineering, construction, or manufacturing companies to achieve the scale required to bid on one of these jobs. Consortia and independent turnkey contracts are generally written on a fixed-fee basis, with the contractor absorbing most of the risks associated with delays or overruns. There are numerous variables that go into determining the optimum contractual formula. In general, the purpose of these packages is to take risk away from the sponsors, while at the same time removing day-to-day managerial control of construction from the sponsor.

Options for a project sponsor: The project sponsor's objective is to establish an organizational framework that lets each participant know what to expect from the others; how to handle changes in cost, schedule, or tradeoff opportunities; how to reach decisions; how to keep the project moving. An effective network of project intelligence and a spirit of "mega-cooperation" must be achieved. Decision-making must be done swiftly and surely, giving prime consideration to the status of the project rather than to the status of the person who sits across the table.

A review of existing megaprojects indicates that there are three generic ways in which owners or sponsors structure their projects. A sponsor's level of involvement is a function of that firm's in-house project management competence. A sponsor can

- Actively manage. Manage the project directly—either as an independent owner or as a partner in a joint venture.

- Direct and control. Contract out the project preparation to consulting engineers and the construction work to contractors or both, maintaining responsibility for day-to-day coordination and management.

- Review and approve. Contract out the complete job to a project manager, a turnkey contractor, or a contractors' consortium. Project management contracts are usually cost plus, while turnkey projects (which delegate managerial or supervisory control to the contractor) are fixed fee, thereby transferring risk to the contractor. In this case, a large contingency fee is commonly added to the price to cover potential risks.

As NASA gets closer to launching the most complex megaprojects of all time, it is important to recognize that sufficient capital, technology, and market access can be pooled from a global network of corporations and financial institutions without compromising NASA's role as the energizing leader with the ennobling vision.

Section 3: Sourcing—and Sustaining—Optimum Financing

> Thanks to our discoveries and our methods of research, something of enormous import has been born in the universe, something, I am convinced, will never be stopped. But while we exhaust research and profit from it, with . . . what paltry means, what disorderly methods, do we still today pursue our research.
> (de Chardin 1972, p. 137)

In words President George Bush quoted from a news magazine, the Apollo Program was "the best return on investment since Leonardo da Vinci bought himself a sketchpad" (Chandler 1989).

Admiral Richard Truly, NASA Administrator, concurs. He believes that no space program on Earth today has the kind of technology and capability that ours does. Our space program is an integral part of American education, our competitiveness, and the growth of U.S. technology. Compared with other forms of investment, the return is outstanding: A payback of $7 or 8 for every $1 invested over a period of a decade or so has been calculated for the Apollo Program, which at its peak accounted for a mere 4 percent of the Federal budget. It has been further estimated that, because of the potential for technology transfer and spinoff industries, every $1 spent on basic research in space today will generate $40 worth of economic growth on Earth.

Spinoffs

Spinoffs from NASA's development of space technology not only provide products and services to the society but also are a significant boon to the American economy. Among the hundreds of examples are this sensor for measuring the power of a karate kick and this thermoelectric assembly for a compact refrigerator that can deliver precise temperatures with very low power input. Estimates of the return on investment in the space program range from $7 for every $1 spent on the Apollo Program to $40 for every $1 spent on space development today.

The critical factor driving productivity growth is technology. The percentage of our national income that we invest in research and development is similar to the percentages invested by Europe and Japan; however, since our economy is so much bigger, the absolute level of our research and development effort, measured in purchasing power or scientific personnel, is far greater than Europe's or Japan's (Passell 1990). But our ability to sustain an appropriate level of investment in R&D is being threatened. We are overwhelmed by our national debt, our decaying infrastructure, and the savings and loan bailout, which alone is expected to cost the Government $300-500 billion, possibly more. To pay these debts would cost each and every American taxpayer between $1000 and $5000, and this is a payment that will not enhance national security, promote economic growth, or improve public welfare (Rosenbaum 1990). This obligation is orders of magnitude greater than the commitments U.S. citizens have made to their space program.

TABLE 18. *Expenditures per Year by U.S. Citizens, Selected Examples*

Expenditure item	Amount per capita
Space station funding, 1990 budget	$23.68
Entire space program, 1990 budget	$55 (approx.)
Apollo Program at peak	$70.00 (1988 dollars)
Beer	$109.00
Legal gambling	$800.00

Source: Sawyer 1989.

We have a military budget of $300 billion (compared to $200 billion per year spent on legal gambling), yet we are too broke to do anything (Baker 1990). Further, our return on investment in research and development is not as effective as it once was. It is possible that military spending is draining critical research efforts; it may be that the American emphasis on basic research has freed Japanese scientists to skip the gritty groundwork and focus on commercial applications; or is it that American corporations may not be good at turning research and development into marketable products? (Passell 1990).

Half of all Federal tax dollars go to the Pentagon. These large expenditures have hurt the competitive position of the United States and have kept the level of investment in the civilian economy, as a share of gross national product, lower than in Europe or Japan. For example, in 1983, for every $100 we spent on civilian capital formation, including new factories, machines, and tools, we spent another $40 on the military. In West Germany, for every $100 spent on civilian investment, the military received only an additional $13. And in Japan, for every $100 spent on civilian investment, a mere $3 was spent on the military. Military spending is 6 percent of GNP, but it pays for the services of 25 to 30 percent of all of our nation's engineers and scientists and accounts for 70 percent of all Federal research and development money, $41 billion in 1988 (Melman 1989).

A "peace dividend" is in prospect, if Congress will cut military spending. A peace dividend offers an opportunity for a political leader to capture attention and resources and do great good. The total dividend through the year 2000 could be as much as $351.4 billion (Zelnick 1990). How the peace dividend should be spent calls into play one's values. Many alternatives are mentioned (the savings and loan bailout, for instance), but NASA is never mentioned as an option.

Under this scenario of declining technological edge, constrained financial resources, and a budgeting process that subjects approved financing to annual revisions and potential cuts, how can NASA adequately source—and sustain—optimum financing?

- Potential sources of funds
- Opportunities for sustainable collaboration
- Life cycle of NASA's funding responsibility

Potential Sources of Funds

The traditional source of financing for any nation's space program is government financing of the national space agency. But government financing alone has proven to be inconsistent and unreliable in the long term, as the space program is forced to compete with other national priorities. Furthermore, as the scale and scope of space projects increase, it becomes beyond the capabilities of a single national government to assume the risks alone—it is effectively wagering national wealth on projects of varying levels of risk.

The stakeholders in the various space development activities can and increasingly should be called upon to participate in the financial risks and enormous potential rewards of innovation that is driven by the "consumers" of Planet Earth, our need for advanced technological capabilities, and our desire to develop livable destinations in space. These stakeholders include

- *The national space agencies* of leading industrialized (and some other) countries around the world typically have a space exploration and development budget representing about 1-6 percent of their GNP.

- *Major corporations and minor entrepreneurial companies* have a new product or process development budget or an exploration budget that is allocated for high-risk, wealth-creating innovative activities.

- *Private investors,* whether individuals or pension funds, have a portion of their savings portfolio dedicated to high-risk, potentially high-return investments in stocks—and even some bonds (i.e., junk).

- *The users of catastrophic pollution-causing products or processes* are recklessly risking the health of our planet in our lifetime—and we are not sure that the damage is reversible. Such reckless users could be assessed a pollution surcharge to fund breakthrough research on nonpolluting new product and processing technologies.

- *National/state/city infrastructure agencies and international development agencies* receive funding to provide particular life support basics, such as water, power, waste disposal, and schools, to their communities or developing nations. A well-honed, functional infrastructure maximizes productivity, enabling the creation of wealth by its residents. Elimination of overlap of effort and global coordination could free up massive amounts of investment money to achieve more effective results.

If these capital reserves were added up per stakeholder category, sources of funds for Planet Earth problem-solving and space development could readily be uncovered in abundance.

Opportunities for Sustainable Collaboration

Examining how these capital resources are allocated, we can readily see that there are billions of dollars being invested in research, design, development, and improvement efforts which overlap and duplicate each other among organizations in the United States, as well as around the world. Many efforts fail to achieve any significant technological advancement precisely because funds are not adequate or scope of authority is not sufficient to make any significant change. For example, if it were decided that automobiles were too heavy, causing the serious deterioration of our nation's infrastructure, and that our automobiles and roadways should be redesigned to achieve a major technological advancement, such an agenda could not be decided on by General Motors alone or the U.S. Department of Transportation alone. Technological advancements of such scale, and more importantly of such global significance, need to be mounted under leadership so engaging and with a vision so encompassing as to ensure that all the key players involved make their capital resources, technological expertise, and access to market demand available to the project.

To take the discussion of our transportation networks one step further, the facts make it clear that the need for technological innovation is not hypothetical but quite real:

- Our national transportation infrastructure has gravely deteriorated, requiring \$3-5 trillion to reconstruct.

- Our auto industry has lost its competitiveness—at home and abroad, and we are struggling to regain a reputation for quality that remains elusive.

- The outlook for transportation vehicles' being able to move about our cities and suburbs at the local speed limit is dimming, as roads are becoming increasingly clogged and overburdened. Such approaches as computerized traffic control screens within vehicles are being tested.

- The carbon monoxide released from combustion engines in autos and their petroleum-based fuels is presenting a grave hazard to the global ecosphere.

- And numerous projects are on the drawing boards around the world to break through our current propulsion barriers, preparing the way to travel at higher rates of speed.

The key players responsible for shepherding such events include the national, state, and city transportation agencies, auto manufacturers, oil production and retail companies, propulsion-focused R&D groups, and automobile buyers and drivers. Their diversity of interest and scope of responsibility and the lack of a single shared vision bodes poorly for formulating an imperative solution to this global time bomb.

An inter-organizational consortium can be formed to address such a problem, whether pertaining to elimination of pollution or development of technology, infrastructure, or resources. Shared risk and responsibility can be established through negotiation and cross-contracting to define the vision, pool capital, share technology, and create market demand of sufficient magnitude to bring such megaprojects to fruition.

Since all prospective players are currently citizens of Planet Earth, the scope of their consortium collaboration can be international as well as national. The scope is determined by the scale of explanatory causes to be uncovered or effects to be achieved through project development. Consortia can be assembled to achieve five possible purposes:

- *Planet Earth protection consortium:* A global R&D fund could be established, supported by taxes assessed on users of pollution-causing products or processes. The funds could be used to identify causes of pollution (thereby further increasing the funding base) or to seed technology innovation that would provide the same effect while preserving the environment (i.e., government-sponsored technological leaps).

- *Technology development consortium:* A mix of designers, manufacturers, and prospective users of a technology should be assembled early on to get the design criteria correct. Seed money could be a mixture of government and private capital. The intent of this consortium would be to involve the companies which would be most likely to develop the spinoff products early, so that their design requirements and insights are fully considered and taken into account. A spinoff surcharge or tax could be assessed as a means of funding the seeding of subsequent generations of research and development.

- *Space exploration consortium:* Exploration is extremely costly and high risk. In the oil business, those who explore and find oil then achieve lucrative payback from either extracting and selling the oil themselves or selling rights to the field. Exploratory missions to neighboring planets could involve a consortium of resource development companies who would be interested in undertaking some of the enormously high risks in exchange for enormously high potential paybacks.

- *Infrastructure development consortium:* It is important that the water, food, power, waste, oxygen, and gravitational systems be compatible in space—to allow for maximum interchange and cooperation among players from diverse nations who might be colonizing space. Agreement on standards is critical to interchangeability of goods and services among participants from different nations. Once standards are set, a vast array of players can begin to develop and market their products and services.

- *Resource development consortium:* Consortia of resource extraction, processing, and manufacturing companies; contractors; builders; equipment suppliers; insurers; and so forth would need to be marshaled to achieve the scale and scope of people and resources required to implement the establishment of a resource-based colony in space. Agreements to fund the costs of installation with loans to be paid back by users or residents of the facility would off-load the burden from the national space agencies to the global business community.

Life Cycle of NASA's Funding Responsibility

The financing required to realize the full array of missions currently on NASA's plate is truly monumental. The exploration projects alone are expected to require more than $60 billion, with more than $100 billion required to operate the various exploratory instruments in space (see table 14) (Broad 1990d).

If NASA's leadership role is to be the exclusive herald of the vision, if its financing role is limited to research and development, and if its charter is clearly defined as syndicating involvement in space exploration and development activities with the private sector, a more realizable long-term agenda emerges (see fig. 14):

- *Phase I (1990-2000): Seed multi-pronged mission initiatives.* This phase requires the greatest amount of independent funding from NASA, but it plants the seeds for user fees and spinoff fees to begin to return in phase II. During the next 10 years Planet Earth monitoring will be initiated; our basic exploration projects will be under way, including the Hubble Space Telescope; more sampling missions will be targeted for the Moon and Mars; heavy funding of the national aerospace plane and controlled ecological life support systems will be provided; and syndication of ownership to enlarge the sphere of producers in space will be promoted.

- *Phase II (2000-2010): Develop an infrastructure support system and do intensive planning.* While some of the initiatives launched in phase I will continue (e.g., Mars sampling missions, capability-driven research), closure on the techniques to be used to support life in space should be achieved. Closure will enable manufacturing companies to begin to produce and market products needed to support humans in space. If these companies were effectively integrated into the early R&D, NASA should begin to collect royalty fees from spinoffs to finance subsequent seed technologies requiring Government-funded nurturing.

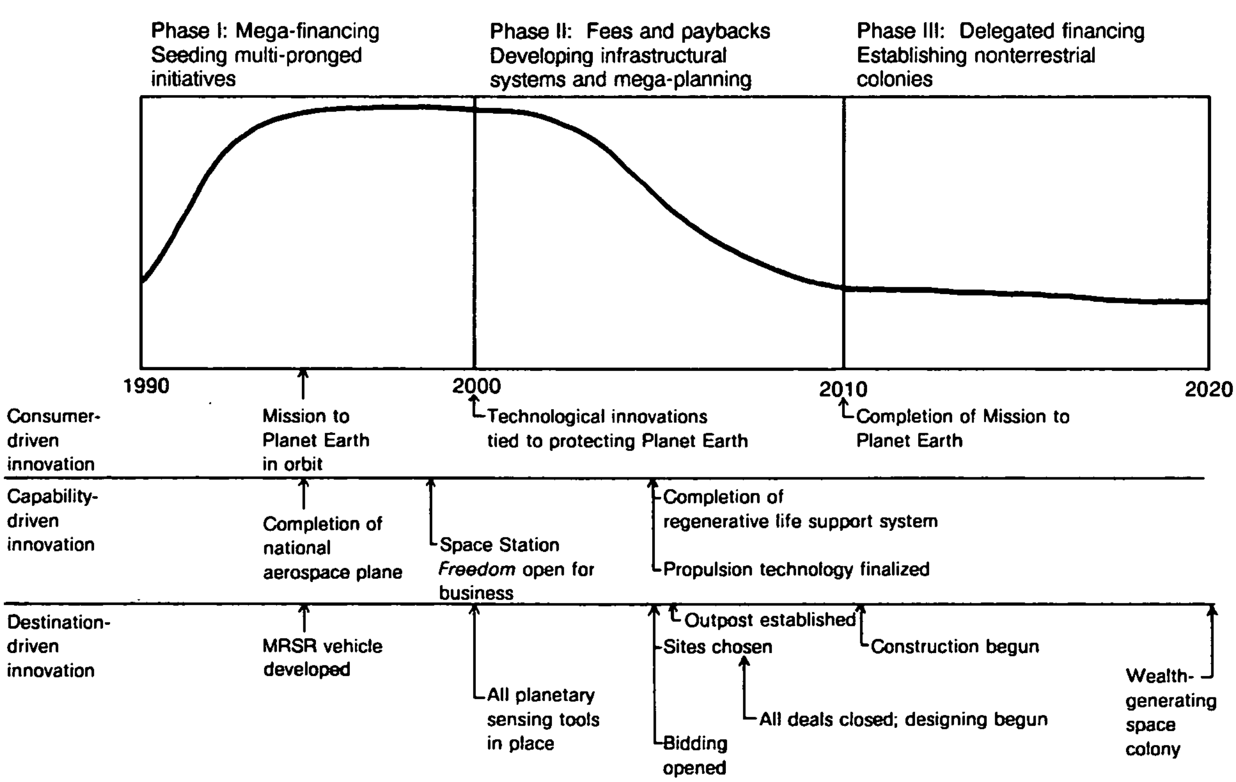
Once the infrastructure technologies and exploration investigations reach closure, mega-planning can begin for colonization of the Moon and

Mars. It will take years to develop detailed designs; negotiate the sharing of risk, responsibility, and rewards; and let contracts. This process may require oversight by NASA, but fees can be charged for bid packages and other services to allay some of the costs.

- *Phase III (2010-2020): Establish colonies on other planets.* This phase should be largely funded by participants, with funds flowing back to the owners and providers of the infrastructure—if it is not an integral part of the project. As colonization begins, products and services—on Earth and in space—should be completely revolutionized, leading to a planetary wealth beyond our wildest imagination: There will be an abundance of resources available from space, new products developed to exploit space, and an abundance of demands that can be met here on Earth as a result of the expanded resource base.

Figure 14

Life Cycle of NASA's Funding Responsibility



We stand at the base of a learning curve that extends to the end of time. The expertise we hold in hand is equivalent to our very first steps, and the targets of our shuffling are most undaring—our closest neighboring planets. Our notions of "high tech" living are being edited daily, as our planetary civilization rushes toward its rendezvous with destiny.

There is new expertise to be honed, new products to be invented, new processes to be engineered. The reality of geotechnology, "which spreads out the close-woven network of its independent enterprises over the totality of the earth" (de Chardin 1972, p. 119), suggests that there is not much point to going it alone—technology is meant to spread like wildfire.

The specific mission objectives sketched out in this paper may not endure; the objectives may change, or from the resulting innovations may come small steps that lead to a higher insight. Advances in our ability to move swiftly and surely up the learning curve are as critical to our future success as our specific achievements. How business systems can be redefined to protect the planet, how technologies can be pushed to their highest performance levels, how new technologies can be created, how sites can be developed in a more humane fashion, how a massive multi-organizational endeavor can be coordinated as if it were a single body, these are the methodologies we are in search of perfecting, equal in importance to the truths we are striving to uncover.

Less than microscopic creatures from the vantage point of the Moon, totally dependent on our 1-pound brains and less-than-1-pound hearts to navigate us toward the unknown and decipher its messages, we human Earthlings have no more powerful resource at hand than our ability to visualize, commit, lead, and actualize—truly incredible abilities that effectively create our future. Our willingness to center ourselves in a common vision—a shared notion of greatness—will abundantly energize us toward fulfillment of even our most elusive goals.

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The Future of Management: The NASA Paradigm

Philip R. Harris

Management Challenges From a New Space Era

The prototypes of 21st century management, particularly for large-scale enterprises, may well be found within the aerospace industry. The space era inaugurated a number of projects of such scope and magnitude that another type of management had to be created to ensure successful achievement. The pushing out of the space frontier may prove to be a powerful catalyst not only for the development of new technologies but also for the emergence of *macromanagement*.

With further extension of human presence into space during the next 25 years, new opportunities will be offered to those responsible for such projects, whether in the public or in the private sector. Satellite expansion, a space station, and possibly a lunar outpost will require new technologies and systems for more complex missions that involve multiple locations and greater numbers and varieties of personnel. Whether in activities of the National Aeronautics and Space Administration, the Department of Defense or military branches, the aerospace industry or new commercial enterprises, there will be a passage from the way space operations have been managed for the first quarter century of development to the way they must be led and administered in the decades ahead.

The challenges will be not just in terms of technology and its management but also human and cultural in dimension (see my paper "The Influence of Culture on Space Developments" in this volume). A recent NASA study, *Living Aloft*, begins to describe the human requirements for extended space flight involving diverse spacefarers (Connors, Harrison, and Akins 1985). In an article on extraterrestrial society (1985), William MacDaniel, professor emeritus, Niagara University, aptly described the multiple challenges in terms of just one undertaking of the next decade—a space station:

> Any way that we look at it . . . NASA will be confronted with management problems that will be totally unique. Space station management is going to be an entirely new ball game, requiring new and imaginative approaches if serious problems are to be resolved and conflict avoided.

MacDaniel, a sociologist and cofounder of the Space Settlement Studies Project (3SP) at his university, then analyzed one people management dimension that results from the sociocultural mix of international scientific and engineering teams and onboard space crews. The multicultural inhabitants of the space station will have to cope with many practical aspects of their cultural differences—differences that alter their perceptions and ways of functioning relative to everything

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from communication and problem-solving to spatial needs and diet. Whether the orbiting of increased numbers of people for longer periods of time is done by the U.S.A. or the U.S.S.R., Japan or Europe, project leaders will have to include managing cultural differences and promoting synergy among their priorities (Moran and Harris 1982).

In any event, futurists, students of management, and those concerned with technological administration would do well to review the literature of emerging space management for its wider implications. NASA offers a paradigm, or demonstrated model, of future trends in the field of management at large.

The Apollo Heritage in Innovative Management

A transformation is under way from industrial designs of organization and styles of management to a new work culture (Harris 1983 and 1985a). In an AT&T report on emerging issues, the term *metaindustrial* was used to designate the new management and the approach to human systems that is evolving (Coleman 1980). One catalyst for this transition may very well have been the inauguration of the space program by NASA around 1960. NASA, in conjunction with its partners in the aerospace business, innovated in more than space technology. Because of the very complexity of the Apollo lunar mission, NASA also invented new ways of organizing and managing.

> The Apollo project which landed a team of American astronauts on the Moon is generally considered as one of the greatest technological endeavors in the history of mankind. But in order to achieve this, a managerial effort, no less prodigious than the technological one, was required.
>
> (Seamans and Ordway 1977)

It is my contention that much of what is currently being characterized as the "new management" is partially the heritage of that space effort, a harbinger of tomorrow's management. This idea is especially pertinent to the building of large-scale technological projects, whether on this planet or in space. Those engaged in complex endeavors that involve many systems, disciplines, institutions, and even nations will have to apply in even more creative ways the legacy that the Apollo program gave to management (Levine 1982). Investigations should be directed to what constitutes *macromanagement*. McFarland (1985) sees this term as meaning "postindustrial management," while I understand it to refer to "the management of macroprojects" (see fig. 15).

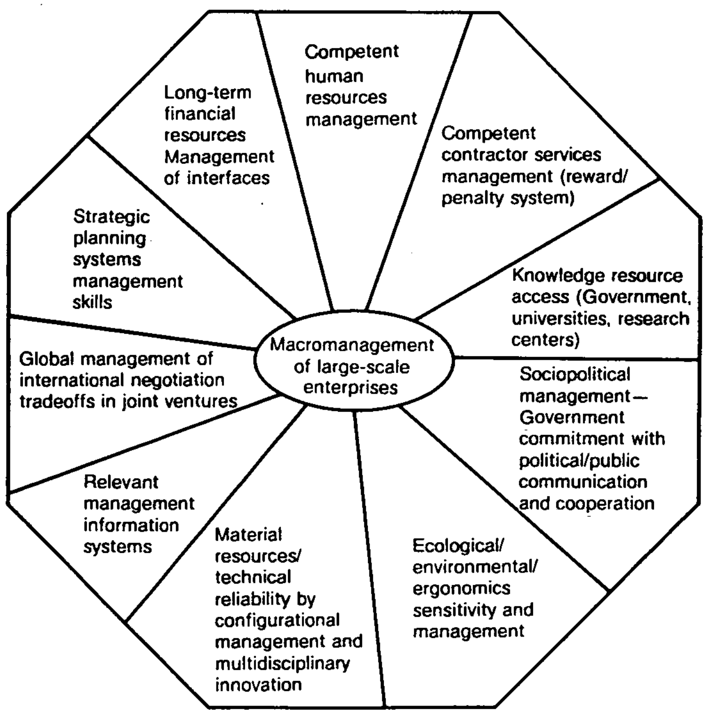

Figure 15

Macromanagement of Large-Scale Enterprises

The management of long-term projects costing $100 million or more will have many aspects. Examples of such "macroprojects" are rebuilding American infrastructure and building a space infrastructure.

In the inaugural issue of *New Management*, the editor listed 10 orientations that lead to organizational excellence today (O'Toole 1983). An organization can excel if it is oriented toward

1. Tomorrow—attuned to the long-term future
2. People—developing human resources
3. Product—committed to the consumer market
4. Technology—employing the most advanced tools
5. Quality—emphasizing excellence, service, and competence
6. External environment—concerned for all stakeholders
7. Free-market competition—imbued with the spirit of risk-taking capitalism
8. Continuing examination and revision of organizational values, compensation, rewards, and incentives
9. Basic management concerns—making and selling products or providing services
10. Innovation and openness to new ideas—nurturing and encouraging those who question organizational assumptions and propose bold changes

Dr. O'Toole was later (1985) to elaborate on this theme in a book entitled *Vanguard Management.*

An examination of the history of the Apollo Program indicates that NASA leaders followed such principles. A possible exception is the third item, which does not quite apply to a public agency, but leaders among the aerospace contractors must have had this concern for the consumer (in this case NASA itself) or the Moon mission would not have been so successful. NASA, over two decades ago, anticipated the emergence of metaindustrial management. The very scope and complexity of putting humans on the lunar surface forced such innovations.

Among the many management innovations to come out of the space program was the matrix organization, with its emphasis on team management. The complexity of the Apollo undertaking necessitated its creation because traditional management approaches proved inadequate. Among the many space contractors, TRW Systems in Redondo Beach, California, was a leader in this process, which was eventually to become a chief feature of the "new" management two decades later. Their vice president at the time, Sheldon Davis, pioneered team building as a means to help technical people work together to reach a common goal (Harris 1985a). Other contractors used the project management and team strategy as a form of ad hoc organization for new starts. General Dynamics, for instance, could quickly assemble experienced team members for its Shuttle-Centaur project from previous work groups that had developed the Atlas-Centaur rocket.

A principal exponent of the matrix as a way of managing complex space projects was Hughes Aircraft. One of its executives, Jack Baugh, did a doctoral dissertation in 1981 on how decision-making is accomplished through a matrix organization. His thesis was that matrix management is essential to an aerospace project when simultaneous decisions are needed in a situation of great uncertainty generated by high information-processing requirements; when financial and human resources are strongly constrained; when the decision-making process must be speeded up; and when the quantity of data, products, and services would otherwise be overwhelming. Obviously, managers outside the space fraternity agreed, adopting the method.

Today a profile of a metaindustrial organization would include these characteristics (Harris 1983 and 1985a):

- Use of state-of-the-art technology, ranging from microcomputers to robotics
- Flexibility in management policies, procedures, and priorities, continuously adapting to the market—a norm of ultrastability (that is, building continuous change into the system)
- Autonomy and decentralization, so that people have more control over their own work space and are responsible for decisions yet work under integrating controls
- Open, circular communication with emphasis on rapid feedback, relevant information exchange at all locations, networking, and the use of multimedia
- Participation and involvement of personnel encouraged, especially through team, project, or matrix management
- Work relations that are informal and interdependent, cooperative and mutually respectful, adaptive and cross-functional

- Organizational norms that support competence, high performance, professionalism, innovation, and risk-taking, even to making allowance for failure occasionally
- A creative work environment that energizes people and enhances the quality of worklife, so that it is more meaningful
- A research and development orientation that continually seeks to identify the best people, processes, products, markets, services, so as to achieve the mission

It is interesting that many of these qualities were identified 15 years ago as essential to the interdisciplinary character of large-scale endeavors (Sayles and Chandler 1971). These were also the characteristics practiced, to a great extent, by NASA management in the Apollo era (Levine 1982). They are considered essential for organizational excellence now and in the future, particularly for large-scale programs such as renewing the American infrastructure or developing a permanent presence in space.

Because those in the management of research and development, especially those coming from engineering and technological fields, may have some misconceptions about the management process, I have included figure 16. This paradigm by R. Alec Mackenzie (1969) illustrates the comprehensiveness of management activity. The conceptual model is a multidimensional approach to the art and science of managing both human and material resources effectively. It highlights, among its central facets, the management of change and differences. This paradigm still seems relevant for managing large-scale undertakings, whether on Earth or in orbit. From my viewpoint as a management psychologist who has served as a NASA consultant, it would appear that the main difficulties facing space management in the future will be found on the right side, in the people dimensions. Unfortunately, this opinion was confirmed by the Presidential Commission on the Space Shuttle Challenger Accident, which concluded that there had been a human systems failure within NASA and its contractors, particularly in regard to information flow and decision-making.

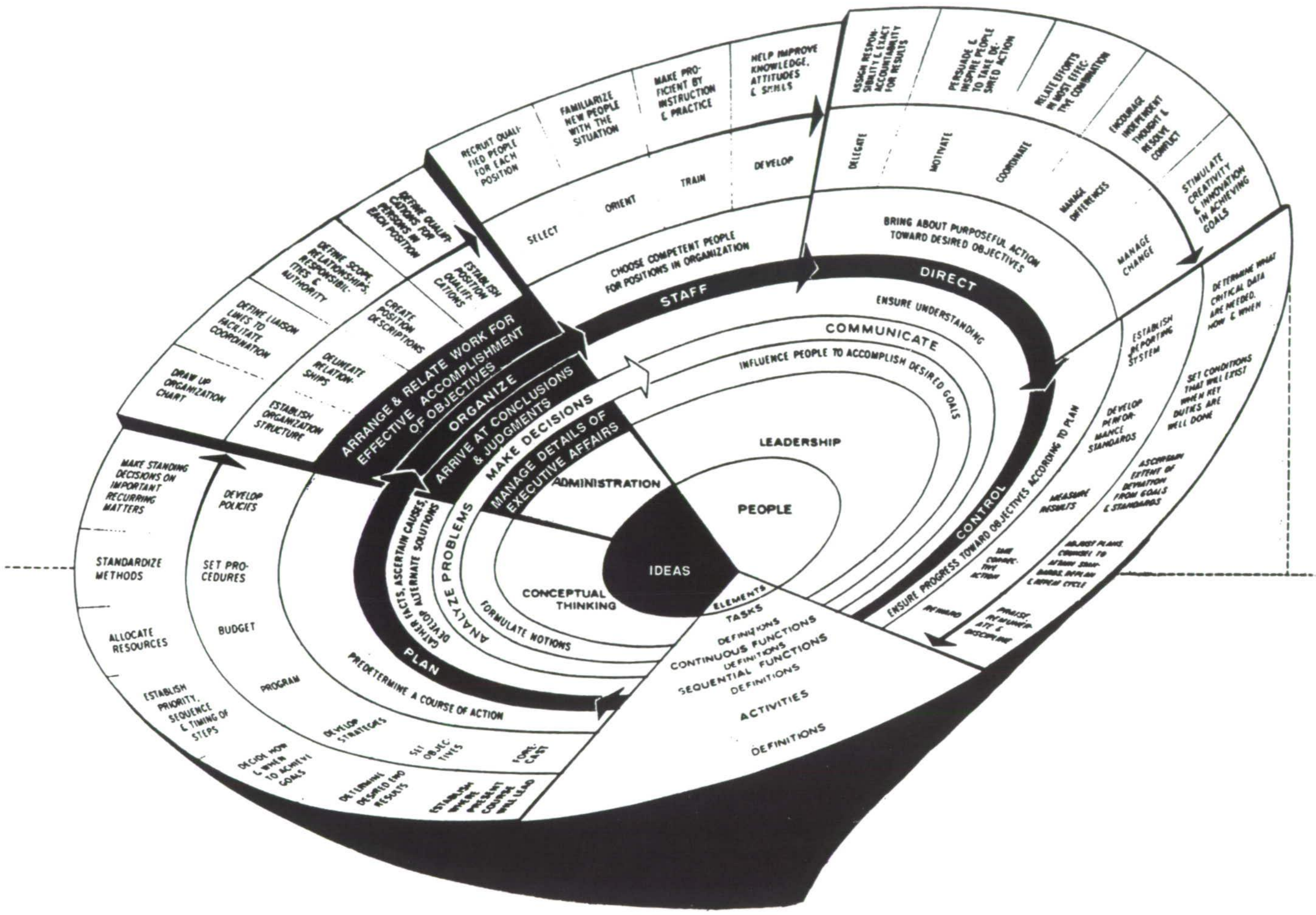

Figure 16

The Management Process

From R. Alec Mackenzie, 1969, "The Management Process in 3-D," Harvard Business Review **47** *(6—Nov.-Dec.): 80-87.*

Perhaps the origins of many 21st century management styles may be traced someday to the 20th century management of research and development institutions. Mark and Levine (1984) make a case for such a thesis by pointing to the Federal Government laboratories that promoted the technology development that resulted in macroprograms like the Manhattan Project, the Apollo missions, and the Space Shuttle. They document both technical and managerial innovations produced by bringing together advanced R&D people in relatively small, quasi-independent groups dubbed "skunkworks." Such groups produced some of the most successful modern aircraft. That form of management was eventually popularized by Tom Peters (1982, 1985) as a central theme of the new management leadership.

The Impact of Organizational Culture

The work culture affects organizational planning, decisions, and behavior. MIT professor Edgar Schein (1985) maintains that the work culture is the mechanism for conveying—explicitly, ambiguously, or implicitly—the values, norms, and assumptions of the institution. Organizational culture is embedded and transmitted through

- Formal statements of philosophy or mission, charters, creeds, published materials for recruitment or personnel
- Design of physical spaces, facades, buildings
- Leader role modeling, training, coaching, or assessing
- Explicit reward and status system, promotion criteria
- Organizational fit—recruitment, selection, career development, retirement, or "excommunication"
- Stories, legends, myths, parables about key people and events
- Leader reactions to or coping with organizational crises and critical situations
- Design, structure, and systems of the organization
- Policies, procedures, and processes

In another paper in this volume ("The Influence of Culture on Space Developments"), I analyze the effect of the organizational culture on NASA and the aerospace industry. Figure 17 is a diagram of space organizational culture, which illustrates the many dimensions of a system's expression of identity. Since research indicates that excellent organizations manifest strong functional cultures, NASA obviously did this during its Apollo period. Has it been doing so in the Space Shuttle phase of its development? The 1986 setbacks and subsequent investigations would indicate a negative response. One outcome of current reorganization needs to be a strengthened NASA culture.

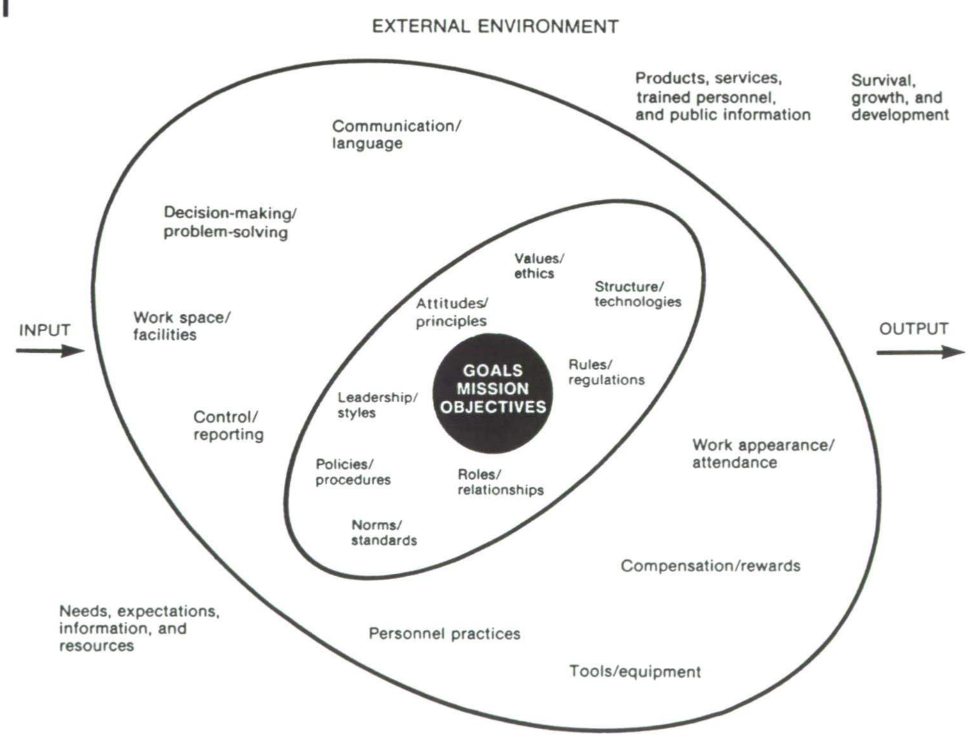

Figure 17

Space Organizational Culture

In 1984, our study team considering space management concluded that a survey and analysis of NASA organizational culture from its headquarters to the field centers would facilitate change and renewal as further space development is planned. If plans for a lunar base are to be effectively implemented, then a transformation in management attitudes, styles, strategies, and operations at NASA may also be necessary. In the post-Apollo era, NASA and its contractors drifted back into an industrial, more bureaucratic style. The work culture, whether of NASA as an organizational system or of its aerospace contract partners, must shift from this industrial or bureaucratic mode back to the mode of enterprises characterized as *metaindustrial*. Only then, it seems to me, will the main actors in the space business be positioned to take advantage of the vast resources on the "high frontier" (O'Neill 1977).

Management consultants see organizations as energy exchange systems. Institutional culture can encourage use of the psychic and physical energies of its people in achieving organizational goals. This is the lesson of the Apollo Moon project. On the other hand, institutional culture can undermine or dissipate the efforts of its people. In order for NASA and its corporate aerospace partners to develop space vigorously in the next 25 years, they must confront the following cultural issues.

(1) The mind-set of the engineer and technologist requires expansion to include generalist thinking. Too often present approaches exclude consideration of human issues, and the contribution of the managerial and behavioral sciences to planning and decision-making are downplayed.

(2) More synergistic relationships in space endeavors should replace obsolete competitive postures by individual companies. The tasks of exploiting space resources are so immense that global space agencies need to collaborate more effectively. Inside NASA, the power games between headquarters and its centers must give way to mutual cooperation. Archaic antitrust regulations must be gotten around to permit aerospace companies to work together to solve common problems, be they matters of quality control on launch pads and space vehicles or greater sharing of

research and development knowledge. The large space corporations can do more for the nation's space program by joint venturing and sharing than by competitive duplication. Furthermore, new ways for synergistic inclusion of university and Government research laboratories should be explored—again as in the Apollo era (Levine 1982). Perhaps the model currently being developed by the European Space Agency is worthy of emulation in North America; it involves cooperation both between nations and between institutions.

(3) As space endeavors reach out to include business participation beyond that of the aerospace companies, attitudes toward and regulations of contractors deserve revision. Perhaps the NASA tradition of partnership with its suppliers is more appropriate than the Department of Defense mentality of seeing its contractors as "users." Space enterprises would benefit from marketplace concerns for satisfying clients and customers (Webb 1985).

(4) Technology development timespans have been lengthened, rather than shortened, because those in the space arena have become more bureaucratic, less entrepreneurial and innovative. From goal-setting to implementation, Apollo's mission was accomplished in less than a decade. Now NASA planners use a 12-to-15-year timeframe from inception to completion of a new technology. Meanwhile, the growing high technology industry (an industry that is a direct spinoff of space technology) has shortened its development timeframe. With due regard to spacefarer safety, perhaps the time has come to reexamine the cultural assumptions by which the practices of redundancy, over-design, over-preparation, over-study, and excessive timidity become embedded habits and traditions. Certainly, such cultural proclivities are less justified in unmanned missions and nontechnical areas, like conference management and reporting. There is reasonable and acceptable risk in the experimental situation of

space flight. What seems more important is effective management of quality control on equipment and parts that go into space transportation systems and habitats.

(5) Organizational renewal implies a continuing process of clarification of roles, relationships, and missions. It requires change from the ways we always did it to the adaptations and inventions necessary to remain a player in the emerging 21st century "space game." Perhaps the habitat modules of space stations and lunar outposts would be better designed by architects and hotel chains than by traditional aerospace vehicle designers. Perhaps the functions of such space facilities should be privatized, so that the NASA centers can take a role more supervisory than operational, thus freeing them for more basic space research and development.

A case relative to cultural issue 2, on synergistic relationships, is the industry-university Consortium for Space and Terrestrial Automation and Robotics (C-STAR). Led by David Criswell of the California Space Institute and sponsored by the NASA-related University Space Research Association, business and academic researchers applying automation and robotics to the space station and other ventures on the high frontier have combined their brain power and established a joint data bank (see, for example, C-STAR Study Group 1988).

The experience with the Shuttle would seem to confirm that NASA moved the project too quickly from research and development into operations. In the transition to 21st century space management, the private sector may dominate the space transportation business and commercial launches, leaving NASA to pursue a technological and scientific research role.

These are but a few of the issues that deserve consideration by management leaders in the space community who would revitalize their organizational cultures and design a management strategy attuned to future demands.

New Roles for Earth- and Space-Based Managers

The five issues just listed are basically cultural and point up the need for planned changes. At our summer study, resource speakers provided numerous suggestions for renewing the American space program and bringing it to new levels of achievement. Several of the more telling comments relate to our topic.

- William E. Wright, Defense Advanced Research Projects Agency, said that the aerospace industry culture is extraordinarily conservative. It suffers from a syndrome: "If it hasn't been done for the last 20 years, forget it." The industry and NASA are not bold enough in their planning and requests for funding. A major program comes into being because someone champions it (puts his reputation on the line and helps bring it into being).

- Peter Vajk, SAI, and Michael Simon, General Dynamics, presented a "stock prospectus" for the establishment of a fictional corporation, "Consolidated Space Enterprises." It envisioned nine companies that could profit by serving customer needs and functions on the space station. Four were providers of such space services as transport, repair, research, and products; three were housekeeping companies that would provide hotel, power, and communication services; two were support companies providing special space services and fuel. The concept of commercial operations on the station, each "feeding" on the other's needs, is not only stimulating to thought but also changes the roles and relationships of public and private participants in space undertakings.

- Peter Vajk, now an independent space consultant, also cited examples of new, more sophisticated management information systems that can alter the role of space project managers. New computer tools, such as relational data base management systems, give managers a better capability to search the literature, while new software like "Hypertext" from Xanadu Corporation (Menlo Park, CA) provides greater access to documentation.

- Ronald Maehl, RCA, pointed out that management issues related to a space station and lunar base represent a departure from traditional NASA management practices. First, there is the matter of managing the development of such projects and precursor missions; then there is the issue of operational management of a space facility when it is functioning. There are precedents in the experience of the National Oceanic and Atmospheric Administration (NOAA) and commercial operators with meteorological and communication satellites. There are new challenges relative to man/machine interactions, operational cost containment, and private participation in such space activities.

These four inputs of experts are but indications of new developments related to the management of tomorrow's space enterprises—developments that warrant more research and call for policy changes by NASA headquarters and its centers. Organizational energy and resources directed to such issues, particularly that of the differences between developmental and operational management, would have greater payoff than the internal struggles of NASA centers to control future programs.

Analysis must be made of the expertise and skills needed by Earth-based managers of projects that are hundreds or thousands of miles away from them. New space project managers have much to learn in this regard from previous project managers of unmanned probes by spacecraft, such as Voyager and Viking, Pioneer and Mariner. The tasks range from limited controls to teleoperations, or the control on Earth by an operator of a machine that is at a remote location such as in space. Management problems experienced include "queuing time" (signal delays between operator command and machine response and between machine response and verification or receipt of data). The management of automation and robotics in space was the subject of another California Space Institute study for NASA (Automation and Robotics Panel 1985).

As more manned space operations occur at more locations, we will need a new infrastructure on this planet to support them. Instead of a single mission control center, there may be regional support centers—some under Government or military auspices and some run by private corporations. For the next 50 years, we are likely to experiment with a variety of Earth-based management plans for space activities, beginning with the space station and a lunar base.

Even more interesting will be management in space of either manned or unmanned ventures. People onsite at a lunar outpost will require more freedom for decision-making and creative problem-solving than the astronauts currently enjoy with mission control in Houston. Decentralized, onsite space management will come into prominence with the building of the space station. Now is the time to begin planning for the practical matters to be faced by station managers, especially when the personnel and organizational components come from various sources beyond NASA itself. In regard to an operational lunar base, research is needed now on such management concerns as communications and leadership and how these functions should be divided between the Earth and the Moon.

Mixed crews (men and women, military and civilian, public and private sector workers, Americans and other nationalities, scientists and other professionals) will invoke more complex management challenges and responses. The people who, in increasing numbers, visit a space station or lunar outpost by 2025 will include more than astronauts or even "astrotechnicians." They will include a broad segment of Earth's society, from politicians to tourists.

In past colonial explorations, trading companies were formed to manage operations in new, remote environs. Perhaps this previous solution could be replicated in a Space Trading Company. If the bold plan for future space developments outlined by the National Commission on Space (Paine 1986) is to be implemented, then more innovative ways for funding and managing space projects will have to be invented. Whether it is financing a fourth orbiter or building a space station, there are historical precedents for national lotteries, selling shares or bonds in space technological venturing, and other forms of public financial participation beyond annual congressional appropriations. The commercialization of space will be a profound force in altering the management of space projects (Webb 1985).

As the crews in tomorrow's space habitations increase in size and heterogeneity, as well as in length of stay away from this planet, planners must expect more stress and strain and must provide space inhabitants with more autonomy, reminds Ben Finney, a University of Hawaii anthropologist, later in this volume. To maximize safe, effective, congenial performance by such pioneers, new programs in behavioral science should be instituted. Studies should be made of team development and group dynamics, new leadership training and responsibilities, and even wellness programs in space communities. Such a program should be part of a planned "space deployment system" I am proposing to facilitate acculturation in a strange, alien, sometimes hostile space environment (Harris 1985b).

For multicultural crews to function well in space, participants must be able to deal with remoteness, they must be self-sufficient and multiskilled, and they must be sensitive to other people and respect the norm of competence. Because space stations in both low and geosynchronous Earth orbit and a lunar or a martian base are such costly, risky, and long-term programs, they will require new management mechanisms that can provide continuity and consistency regardless of personnel changes.

Another management concern to be addressed more vigorously is that of multipurpose missions, such as one involving both civilian and military payloads (Brooks 1983). Economies of scale and piggybacking to contain costs are arguments for combined missions. Technical and management complexity and the issues of secrecy, foreign policy, and international cooperation may prove stronger cases for keeping commercial and defense space activities separate.

Space management would seem an ideal subject on which the Academy of Management and other scholars should focus their research and conferences.

Macromanagement in Space

As has already been indicated, large-scale and complex technical programs require a new type of macromanagement, whether to rebuild this planet's infrastructure or to create a space infrastructure. Figure 15 offers an illustration of the scope of such an undertaking from a management perspective. Long-term projects costing $100 million or more require the application of administrative skills across a range of activities that begins with strategic planning and extends to global or interplanetary management of material and human resources.

Macro-engineering projects have shaped our past and may well shape our future (Davidson 1983). Space programs, like Apollo and the Shuttle, have advanced the field and may be the force behind growth in an allied discipline—macromanagement. Most space programs are macroscopic because they share these characteristics:

(1) They involve difficult, complex engineering and management problems which must be resolved before the program is completed.

(2) They require significant public and private sector resources that must be committed over long timeframes.

(3) They include scientific and technical problems of unusual complexity, size, or circumstances, and the solutions often involve previously unknown technologies or resources.

(4) They have profound impacts on the environment, legal and regulatory situation, economics, and politics of the societies that develop them.

(Davidson, Meador, and Salkeld 1980)

Project management of large-scale enterprises has benefited from such new tools as the program evaluation and review technique (PERT), the critical path method (CPM), and project management space systems (PMSS) modeling. Developments in the supercomputer, software packages, and management information systems have made macroprojects more feasible and manageable. Many of these management innovations owe their origins and refinements to the Department of Defense and NASA.

Macromanagement of large-scale enterprises may very well become a dominant theme in 21st century management practice (McFarland 1985). As NASA seeks to implement plans for a space station in the 1990s and a lunar outpost by 2010, it will not only have to use macromanagement strategies, it may also pioneer in the process. As more corporations participate in space ventures rather than just those in the aerospace industry, NASA will face a new set of interface challenges with these new stakeholders. Already space entrepreneurs expect to launch satellites and a variety of other commercial space ventures that require creating synergy with NASA (Webb 1985). Some of these space enterprises will necessitate the adoption of macromanagement methods.

Research funding should be directed into matters of macromanagement by NASA, global corporations, universities, and others because it demands a new type of management thinking, style, and skills. For example, macroprojects, whether on Earth or in space, stand in need of leadership capable of

- Synergy—facilitating cooperation and collaboration in bringing together diverse elements, so as to produce more than the sum of the parts

- Intercultural skill—overcoming differences between peoples, groups, and nations, particularly through effective cross-cultural communication and negotiation

- Political savvy—gaining agreement and support for project goals from the various political or governmental entities, as well as from the public if their support is essential

- Financial competence—understanding the economic realities of a long-term project and capable of putting together the necessary funding to complete the undertaking, while containing excessive expenditures

- Interface management—taking the lead in bringing together on time the various resources (human, informational, technical, material) required to achieve project goals

- Cosmopolitanism—sensitive to global and interplanetary issues affecting the project, such as legal, ecological, environmental, and human concerns, and able to cope with such issues from an international rather than a national perspective

These are but a sampling of the qualities that are desirable in the new macroproject executive or manager. Perhaps no one person possesses all of them, but a management team may exercise such competencies together. Certainly, a traditionally educated engineer is not likely to possess many of these skills. Research on the education of macro-engineers has been under way at MIT under the conduct of Frank Davidson, and it is beginning at the University of Texas' Large-Scale Programs Institute under the direction of George Kozmetsky. Publications such as *Technology Review*, published by MIT Press, are also addressing these concerns. These efforts should be expanded to include macromanagement as a subject of study. Kozmetsky (1985) calls for transformational management strategies, thus indicating that macromanagement may be one of the central issues of 21st century management.

During our summer study, two resource speakers pointed out existing management models worthy of further analysis by space planners. To create the necessary infrastructures for tomorrow's space programs, consultant Kathleen Murphy (1983) proposed that we could learn from large development projects around the world. (See her paper in this volume.) Such major "greensite" projects have already resolved problems between owners and contractors—developing techniques of conflict resolution and negotiation and making reward and penalty provisions. And they have tested financial arrangements that might prove feasible for space development—including new financing models, joint ventures, consortia, R&D shared between Government and industry, and national bank syndicate investments.

The other input came from consulting engineer Peter Vajk, who observed that global projects concerned with new terrestrial materials may offer insights into the exploration for and exploitation of space resources. Like NASA projects, these projects are high-risk and capital-intensive. They involve very large costs for research and development, startup, and operations. They are beginning to use a macromanagement approach in which a corporate headquarters sets general policy, negotiates major contracts, and keeps accounting and systems records, while subsidiary facilities operate under distributed or semiautonomous management. Projects in new terrestrial materials, being technology- and skill-intensive, involve macro-engineering. They own, lease, or hire their transportation. They operate distribution centers, retail outlets, and sales offices. Their programs are extended in time and space throughout the deployment and operation phases. Their activities are transnational. They use sophisticated computer information networks involving high-rate data transfer. Vajk believes that macroprojects to develop nonterrestrial resources can operate like these Earth-based analogs: "Space is just a different place to do the same kinds of things we do on this planet."

But space is a place for large-scale endeavors of a peaceful and commercial nature. It opens opportunities for human institutions and governments to produce synergy, not war. It requires not only new mind-sets but new management. Over a decade ago, a classic work provided us with a charter for that purpose. In *Managing Large Systems: Organizations for the Future* (1971), Sayles and Chandler reminded us that such enterprises are interdisciplinary in character and integrate an array of scientific, technological, social, political, and other personalities and resources. This charter describes the large-scale programs of NASA, as was well understood by the key administrators of the Apollo Program.

In 1986 the National Commission on Space, appointed by the President, issued a report, *Pioneering the Space Frontier*. It recommends spending $700 billion on the U.S. space program for manned settlements on the Moon within 30 years; a new generation of spacecraft that could voyage to the Moon, Mars, and beyond; and a new space infrastructure for interplanetary factories, spaceports, and communities to accommodate eventually one million space travelers a day. Macroprojects, such as will be undertaken in space by the turn of this century, need more than bold vision; they need a system for managing continuity over long periods, despite fluctuations in personnel, policy, government administrations, and finances. Gaining a national consensus to support new space ventures is a cultural problem. Implementing plans for that purpose implies innovative approaches to space management, such as have been discussed here.

For existing space organizations, such as NASA and its aerospace partners, reeducation of personnel is in order to prepare for the future demands of space management in general and macromanagement in particular. New executive and management development programs should be designed to deal with these considerations. Technology or R&D managers need to become more general in their outlook, more open to new ideas outside their own fields and industries, more competent in management skills. For this to happen, schools of engineering and business will have to design joint curricula, while corporate specialists in human resources and development will have to cooperate with R&D professionals to create more appropriate in-house training.

Space management in the future will necessitate crossing traditional academic disciplines and industrial fields, as this quotation of Frank Davidson (1983) so succinctly implies:

> Space development is a critical case-in-point, because it will test the ability of our diverse, rather relaxed society to set long-range goals, to hue [*sic*] the line despite disappointments and setbacks, and to devise institutional arrangements that will assure continuity. . . . Low-cost approaches are indispensable, because an increasingly educated public will rightly insist on [a] return on investment. . . . Now is the time, therefore, for the aerospace community to reach out to the mining industry, the heavy construction industry, and the ground transportation industry, so that joint ventures on land and sea, as well as "up there" may set a pattern of partnership and a network of personal relationships which will benefit all systems engineering programs that are so necessary for the future health, safety, and prosperity of the Republic.

Conclusions

Under the leadership of NASA, plans are being made for space developments in the next 25 years. At a minimum, the program will include space and lunar stations that will be complicated to construct and manage, require a new generation of technology, and cost billions of dollars. From these bases in space, planners envision mining the Moon, possibly mining an asteroid, and eventually launching manned missions to Mars (maybe a joint mission with the Soviets). Such developments will require an organizational transformation of the National Aeronautics and Space Administration. This may involve structural changes that give the agency more autonomy and flexibility, especially long-term financing. Certainly, it should include planned organization renewal so that NASA builds on the technological and management innovations of its Apollo heritage. If the national decision is to go to Mars jointly with the Soviets, then the challenge will be the integration of the two countries' space management systems.

To become and remain fully metaindustrial, NASA and its aerospace partners will have to create a new work culture. For that purpose, I have proposed a survey and assessment of their current organizational culture, so as to ascertain what changes are necessary for future space management. For NASA, the management changes involve new relationships with the military and the private sector, as well as with international space consortia and possibly some new entities, such as a global space agency.

Obviously, the next 25 years in space will also alter the way we manage enterprises in space. Initially, we need more research on issues of leadership for Earth-based projects in space and space-based programs with managers there. The days of the traditional "mission control" may be waning. Second, we need to realize that large-scale technical enterprises, such as are undertaken in space, require a new form of management. Therefore, NASA and other responsible agencies are urged to study excellence in space macromanagement, including the necessary multidisciplinary skills. Two recommended targets are the application of general living systems theory (Miller 1978; see also his paper in this volume) and macromanagement concepts (McFarland 1985) for development and operation of a space station in the 1990s. Such management models may supply the positive orientation now needed in planning America's aerospace future.

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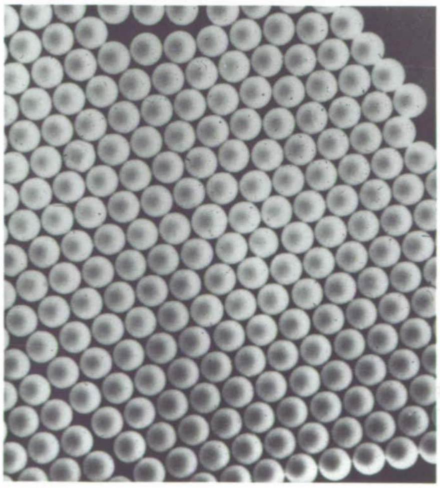
Space Law and Space Resources

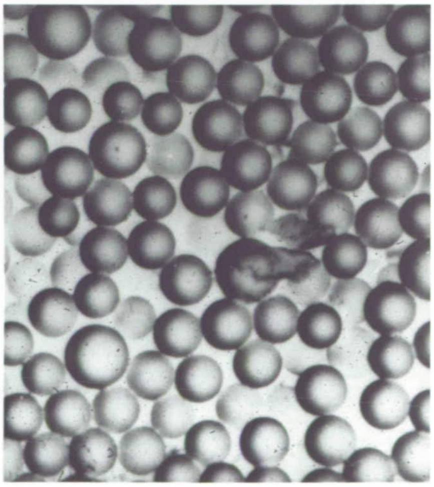
Nathan C. Goldman

Law is not immutable; it responds to the needs of society. Since World War II, humanity has moved increasingly into outer space, encountering new conditions and new needs along the way. The law of outer space has addressed the new political, economic, and technical needs that accompany this transit of human society into space. Space law has been expressed in broad, vague principles that have permitted the maximum flexibility necessary for exploratory space activities. But, as exploration gives way to settlement, this predominantly international law lacks the specificity and legal certainty necessary for mature commercial activity.

Space industrialization is confronting space law with problems that are changing old and shaping new legal principles. Manufacturing in space and exploiting nonterrestrial resources pose economic and political issues that the nations must address. Space exploration has been conducted in the names of peace and humanity; yet, the increasing awareness of the value of space exploration and space applications dictates a new consideration of the merits of international competition and international cooperation in space.



(a)



(b)

Space Manufacturing

a. Latex beads produced in the microgravity of space

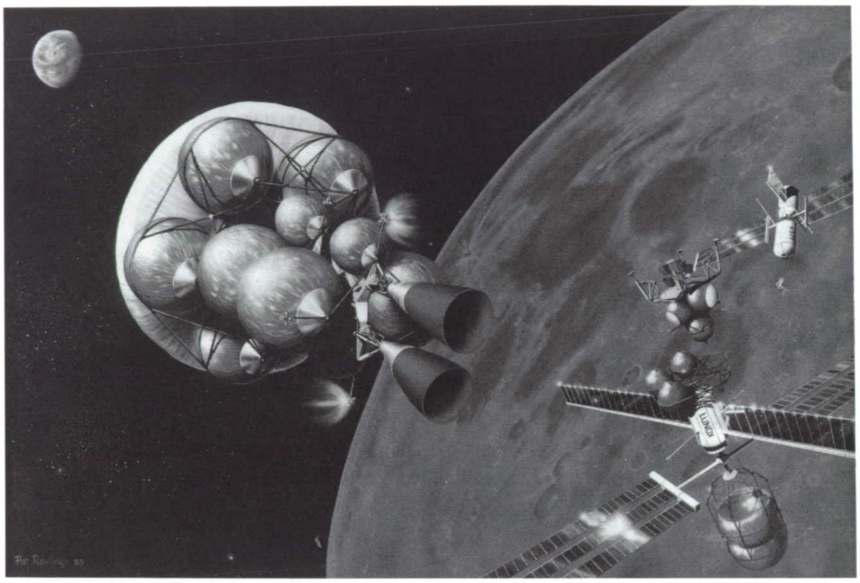
b. Latex beads produced in Earth's gravity

In the microgravity of low Earth orbit, perfectly uniform spheres of latex can be manufactured. Compare these produced on the Space Shuttle (a) with those produced on Earth (b). Note that the products influenced by gravity are of different sizes and sometimes deformed.

Shipping Lunar Oxygen

In this concept, based on a model by Hubert Davis of Eagle Engineering, a lunar lighter is delivering oxygen produced on the Moon to the LUNOX propellant storage depot in lunar orbit. A lunar freighter, equipped with an aerobraking heat shield, is leaving the storage depot carrying oxygen to low Earth orbit for use as propellant on outward bound journeys. On the other end of the storage depot are two larger tanks of hydrogen for use in the manufacture and shipment of lunar oxygen. In orbit with the LUNOX platform is a small space station providing support to lunar astronauts.

Artist: Pat Rawlings



It is given that nations must pursue their national interests. The policymakers in the United States have not always considered well the national interest in space. This lack of policy sophistication resulted in part from arrogance over the American lead in space and in part from ignorance of the importance of space in the future balance of power. Today, with our dwindling lead and with the growing importance of space, the United States must negotiate its international space agreements with the same concern for national priorities that it has in any other international arena. Of course, in any given situation, either cooperation or competition may better serve the national interest.

The Treaties

The U.N. Committee on the Peaceful Uses of Outer Space (UNCOPUOS) is responsible for the major portion of international space law. It has negotiated five treaties. The first four, from 1967 to 1976, have been ratified by the United States, the Soviet Union, and many other nations, active and inactive in space. The fifth treaty, the Moon Treaty, was ratified by the U.N. in 1979 but has been ratified by only seven nations, none of whom has an active space program.

The first treaty, called the Outer Space Treaty or Principles Treaty, has been ratified or acceded to by almost 100 nations. Its broad principles provide the foundation and the philosophy for activities in outer space—that is, a commitment to explore space in peace and for the benefit of all humanity. The second, 1968 treaty—the Agreement on the Rescue of Astronauts, the Return of Astronauts, and the Return of Objects Launched Into Outer Space—expands on the 1967 principle that astronauts are the "envoys" of humanity who should be honored and assisted in every respect (U.S. Senate 1978).

Space Station Emergency Rescue Vehicle

This design is one of several being considered to provide a safe and reliable emergency return from the space station. The Assured Crew Return Vehicle (ACRV) would be based at the space station and use de-orbit engines to return to Earth.

Rescue capability would be offered to astronauts of any nation, as in September of 1988 the United States offered tracking and recovery help to the Soviets when their cosmonauts, Russian pilot Lyakhov and Afghani copilot Mohmand, had difficulty returning from the Mir space station in a Soyuz spacecraft.

Artist: David Russell

Ratified in 1973, the Convention on International Liability for Damage Caused by Space Objects spells out many of the liabilities and duties of spacefarers and describes a procedure to enforce these obligations. The final major treaty, the 1976 Convention on the Registration of Objects Launched Into Outer Space, expands on the 1967 principle that nations retain jurisdiction over and responsibility for their facilities and objects in space. It mandates that a nation register its launch with a U.N. Registry, and thereby legitimate that nation's jurisdiction over the vessel or facility.

Skylab Is Falling!

Lou Pare, flight controller, marks an area in the Atlantic Ocean, part of the final "footprint" of Skylab, as Gene Kranz, deputy director of flight operations at the Johnson Space Center, looks on. Skylab, America's first space station, was launched in 1973 and served as home for three crews, during 1-month, 2-month, and 3-month stays in 1973 and 1974. The spacecraft (which was not designed to be restocked) was turned off, its orbit decayed, and it broke up as it reentered the atmosphere July 11, 1979. Most of its pieces burned up in the atmosphere. Of the pieces that survived the heat of reentry, most fell into the ocean. Only a few fell on land (some were recovered in Australia); none caused any damage.

The 1979 Moon Treaty builds on another 1967 principle, space for the benefit of mankind, to dictate an international regime that will be established at a future date to regulate space resources "in place," declared now the "common heritage of mankind." Neither the United States nor the Soviet Union is likely to sign this treaty. Nor is the treaty likely to gain wide acceptance, authority, or standing as law. Nevertheless, the treaty does represent the most complete international effort to date to deal with the legal and public questions of colonizing and exploiting space.

This thumbnail sketch of space law has been neither comprehensive nor detailed, but it provides a background suggesting serious legal-political problems that will confront the first efforts to mine and use the resources of the Moon and other celestial bodies (Goldman 1988).

Treaty Issues

The utilization of space resources will raise many issues that diplomats and international lawyers need to consider. This section identifies only four of these issues: (1) international competition and cooperation, (2) property rights and nonterrestrial mining, (3) legal liability and responsibility, and (4) environmental impact.

International Cooperation

International cooperation is a theme that pervades the legal regime of space. According to the 1967 Outer Space Treaty, space is to be used for "the benefit of mankind" (Article I). Nations cannot annex or appropriate outer space or the celestial bodies (Article II). The United States has always balanced these more altruistic principles against a second theme: nations are permitted by the treaty to "use" and exploit space. As participant in the negotiations and ever since, the United States has always argued that nations can mine and claim resources "in place" even under the 1979 Moon Treaty (Christol 1982, pp. 293-296).

Photo (just after the start of the run into the Cherokee Outlet, September 16, 1893): L. D. Hodges

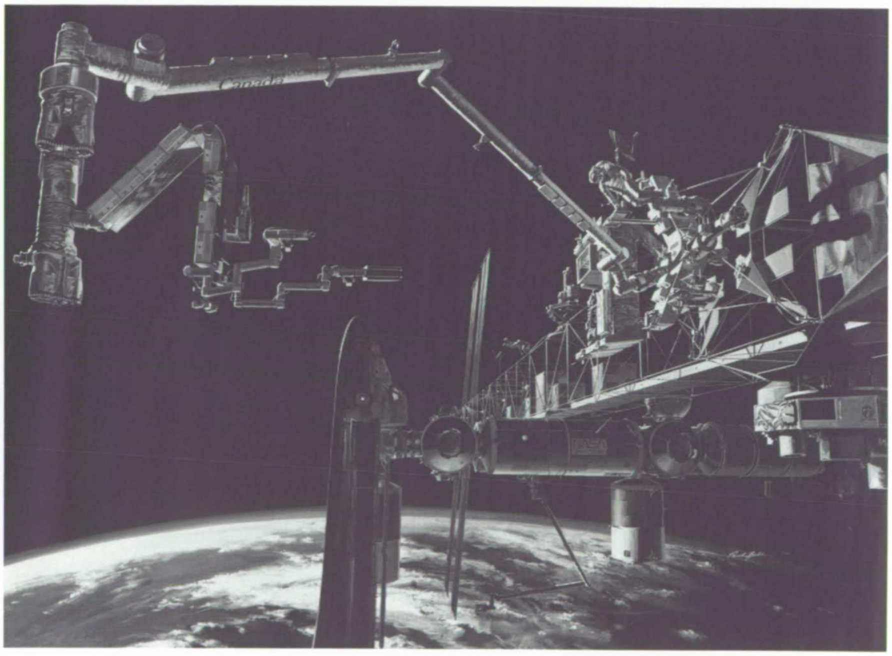
Provided by the courtesy of the Archives & Manuscripts Division of the Oklahoma Historical Society.

Oklahoma Land Rush

On April 22, 1889 (some a little sooner), 15 000 settlers from 32 states lined up to make a run into the unassigned lands of the Oklahoma Indian Territory and stake claims to homesteads. Within 5 days a tent city had sprung up on the prairie at Guthrie. International law prohibits the staking of claims to lunar territory, but nations who can get there can use the resources onsite. The United States has always maintained that under the 1967 Outer Space Treaty, which it signed along with almost 100 other nations, and even under the 1979 Moon Treaty, which it has not signed (nor has the Soviet Union), lunar settlers would be able to mine and claim the resources at a lunar base.

Provided by the courtesy of the Western History Collections, University of Oklahoma.

Of course, separate from the legal issue, the United States will need to make a political decision whether to proceed alone or in consortium with other nations. Such cooperation may offset opposition to its activities from many governments, especially in the Third World. Cooperation spreads the risks and the cost of the program; all partners gain from the expertise of the others. Then, the partners can share the technical and financial riches of so momentous an undertaking.



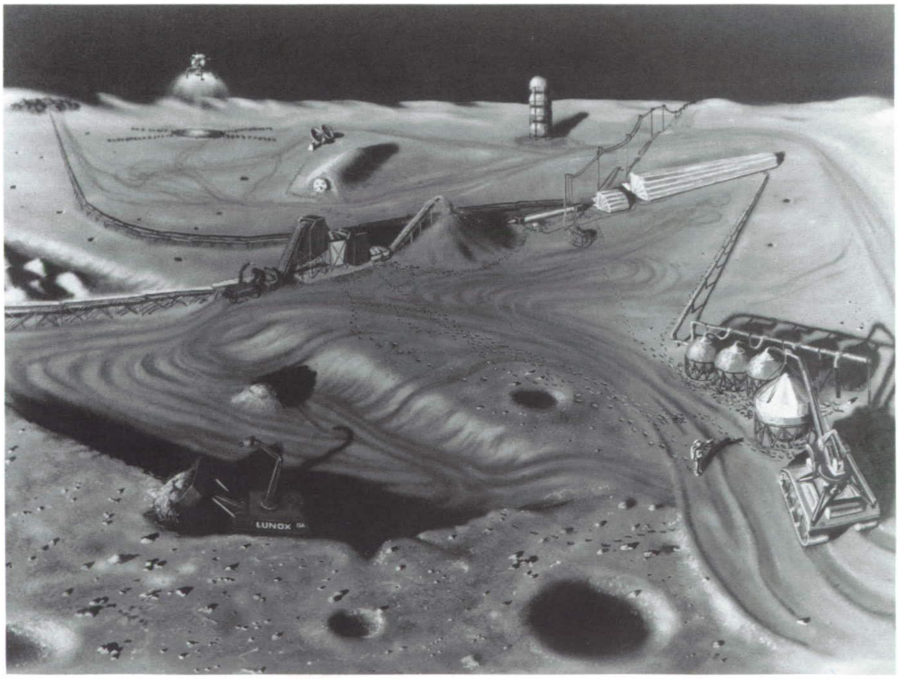
***International Cooperation in Space Station* Freedom**

Cooperating with the United States in the construction and use of Space Station Freedom *will be Canada, Japan, and the nations of Europe. The U.S.A. will supply the habitat module and one laboratory module; the European Space Agency (ESA) will supply a second laboratory module; the Japanese, a third. Canada will supply a mobile servicing center, which will include an improved version of the remote manipulator arm currently in use on the Space Shuttle. It will help assemble the space station and will provide grappling capability thereafter. Such international cooperation spreads both the costs and the benefits of space development. All the partners gain from the expertise of the others.*

Artist: Paul Fjeld

Mining

According to present space law, all mining in space—lunar, asteroidal, or planetary—is treated alike. The operative treaty provisions are (1) that space is reserved for the benefit and is the province of all mankind; (2) that every nation shall have equal access to outer space; (3) that nations cannot appropriate space under any claim of national sovereignty; (4) nevertheless, that nations are free to explore and "use" outer space. The official position of the United States, clearly enunciated in the debates of UNCOPUOS, interprets these provisions to permit any nation or corporation to mine and otherwise use the resources of outer space.



Lunar Mining and Processing

Though international law prohibits the annexation of any part of the Moon, it would allow the use of raw materials mined at a lunar base. In this concept, based on a model by Hubert Davis of Eagle Engineering, bulk soil from a strip mine is delivered by front-end loaders to an automated processing facility. The oxygen won from the process is liquefied and piped to the storage tanks on the right. One filled tank is being loaded now, perhaps to be used at the lunar base, perhaps to be shipped to orbit. The slag is carried by conveyor belt to a dump in the background to the left. Near it, a lunar lighter can be seen landing. The tanks stacked to the right of the buried habitat module contain hydrogen for use in the process and as propellant. Power lines stretch over the ridge to a power station, possibly a nuclear reactor.

Artist: Pat Rawlings

Even under the rather anticapitalist Moon Treaty, the official position of the U.S. negotiators in UNCOPUOS has been that the treaty permitted companies and nations to mine the Moon. For instance, light elements—hydrogen, nitrogen, and carbon—exist in limited quantities in the lunar soil, and frozen water may exist in larger amounts at the lunar poles. Under the longstanding U.S. legal interpretation, the nation finding these resources will be able to mine them. The nation will not own the site, but its labor will attach ownership to the ore (Christol 1982, pp. 39-43). American legal and political planners need to consider the scenario in which spacefarers from another nation go to the Moon and find a singular deposit of volatiles.

American negotiators of the Moon Treaty have argued that the treaty language prohibiting ownership of space resources "in place" means that when the resources have been removed from "in place," personal labor attaches and the mining concern would own the extracted materials. The treaty also envisions that the signatory nations would "undertake" to establish an international regime when utilization of space resources becomes an active possibility. By analogy to the international regime described in the Law of the Sea Treaty (which transfers technology and proceeds from the resource developer to nonparticipants), the regime for space has been vilified by many writers and politicians, and this was a major issue in the defeat of the treaty. The interpretations of the U.S. negotiators evoke alternative regimes, including an international investment organization which nations could join if they desired. Intelsat, the International Telecommunications Satellite Consortium, is such a model.

Although much of the world will object, the legal bottom line on mining nonterrestrial resources is that the United States, the Soviet Union, or any other nation that can get there can mine the Moon and other celestial bodies.

The case of the near-Earth asteroids, however, raises a trickier legal issue. Although a nation cannot appropriate a celestial body, it can use the resources. If space mining basically consumes an entire, small near-Earth asteroid, has the "use," become an "appropriation" of the celestial body? This situation appears to be another example in which the technologies have rendered the treaties obsolete. Perhaps the diplomats need to amend the treaties to redefine these smaller asteroids as a different class of celestial bodies.

Liability and Responsibility

According to the 1967 Treaty, nations are responsible for the space activities of their nationals (Article IV). The Liability Convention in 1973, moreover, established an absolute liability for damages on Earth caused by space activities. Liability based on fault is authorized for damage in space (Article II). Therefore, if the United States decides to take in private industry as a partner in transporting or mining, the U.S. Government would have to monitor these partners closely.

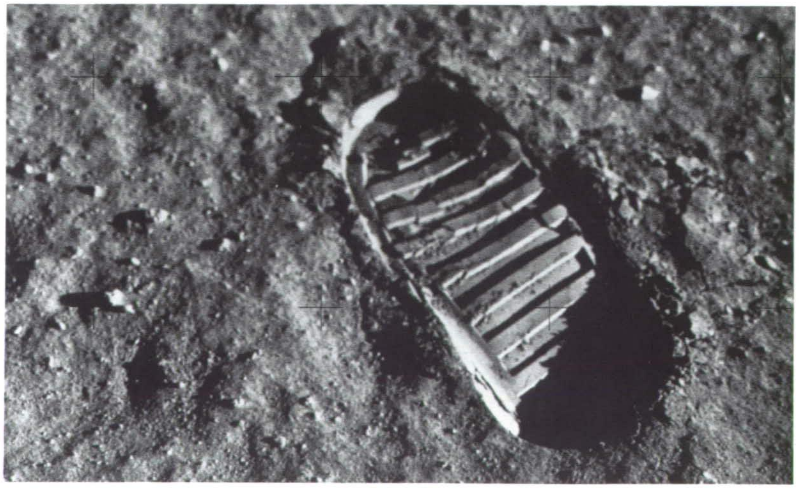
The Liability Convention also provides that nations are jointly and severally liable for damages caused by their cooperative space effort (Articles IV and V). Although the memorandums of understanding or treaties among these national partners will apportion liability and provide a mechanism for settling disputes, the bottom line remains that one nation may be held liable for the entire accident.

Environmental Impact

Two broad concerns for space resources and environmental impact raise treaty issues: (1) back-contamination of Earth and (2) environmental protection of the celestial bodies. The Outer Space Treaty requires consultation about the environmental issues (Article IX). The Moon was seen as sterile, and the rules for back-contamination were not as strict as many scientists wanted. Mars and other celestial bodies may require a different set of regulations. The unratified Moon Treaty suggests that nonterrestrial sites of scientific interest should remain pristine.

Should the Moon Remain Pristine?

"That's one small step for a man, one giant leap for mankind," said Neil Armstrong as he set foot on the surface of the Moon July 20, 1969. His footprints, those of fellow explorer Buzz Aldrin, and the footprints of the 10 other Apollo astronauts to walk on the Moon remain clear and sharp on this windless satellite, despite the passage of 20 years. In fact, the footprints of these astronauts will likely last about 1 million years before they are eroded away by micrometeorite impacts. Development of such nonterrestrial sites will create further disruptions. Where should the line be drawn between protecting the environment and developing the resources?



Strategies for Broadening Public Involvement in Space Developments

Philip R. Harris et al.

Rationale

There is widespread public interest in and goodwill toward the space program. For NASA's plans for the next 25 years to be achieved, this public reservoir of support needs to be tapped and channeled. NASA endeavors have to reach out beyond the scientific, technological, and aerospace communities to foster wider participation in space exploration and exploitation. To broaden NASA support and spread out the financing of space activities, we offer these recommendations for consideration.

Economic

For anticipated space missions to be carried out, new sources of income and financial participation should be sought. NASA can no longer operate merely on the basis of annual Federal appropriations. A national commission of financial experts and venture capitalists might be established to analyze the alternatives, recommend to the President and Congress policies and procedures for the public sector, and propose space investments for the private sector. These are a few of the options to be analyzed:

(1) A national or international lottery

(2) A national bond issue

(3) A stock investment plan

(4) Limited partnership opportunities for space technology

(5) Joint ventures by NASA with other national space agencies or with multinational corporations

Political

To create a national consensus and ethos for space development in the next 25 years, NASA should exercise vigorous leadership on behalf of its intended missions. For this purpose, the following program is recommended to educate politicians, as well as the public, in the scope, necessity, and value of space plans.

NASA needs to decide among the alternative scenarios for space development up to 2010. A plan with specific goals, time targets, and estimated costs, including locations in space and required technology, should be summarized in a case for investment, which is then communicated to all NASA constituencies through a variety of modern media. Using the journalistic who, what, when, where, why, and how as a framework, this case could be put forth in publications, films, videos, and public presentations. To carry this message to the point where

Conclusions

The return to the Moon, the next logical step beyond the space station, will establish a permanent human presence there. Science and engineering, manufacturing and mining will involve the astronauts in the settlement of the solar system. These pioneers, eventually from many nations, will need a legal, political, and social framework to structure their lives and interactions. International and even domestic space law are only the beginning of this framework. Dispute resolution and simple experience will be needed in order to develop, over time, a new social system for the new regime of space.

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public support is transformed into financial contributions, we recommend that NASA focus on the space station, a lunar base, and unmanned explorations, especially of Mars, for the next quarter century. Special briefing workshops might be held for the members of the House and Senate and their staffs, the media, and business leaders. Emphasis should be on the commercial promise of space.

Mars Rover Sample Return

Just as the Apollo lunar samples have been the cornerstones of our knowledge base for planning human habitation and exploitation of the Moon, so martian samples should greatly enhance our ability to plan for exploration of Mars. Analysis of martian rocks and soils would help determine what chemical resources (water-bearing minerals?) are available and what scientific questions human explorers should be prepared to investigate. Plans are currently being made to send robotic sample collectors to several spots on Mars. In this concept, a six-wheeled rover collects and packages samples and delivers them to the launch vehicle in the background which will return them to Earth. Each rover/launcher combination could probably provide about 5 kilograms (11 pounds) of samples. Sample returns from various sites on Mars could help select the sites that could be explored with the greatest benefit. In particular, knowledge about martian rocks and soils could help us prepare the tools and techniques to search for evidence of past life on Mars.

Artist: Ken Hodges

The following means or sources of assistance should be examined:

(1) A White House conference on space enterprise, called by the President at the request of Congress, to consider how to implement the 1986 recommendations of the National Commission on Space. The provisions of the Space Settlements Act (H.R. 4218) might be added to the agenda for discussion. The proceedings could be televised by the Public Broadcasting System and later published in book form for wider dissemination.

(2) A national convocation by NASA of all space organizations, associations, and societies to enlist their support for the NASA plan and to obtain recommendations for private sector involvement in space developments. In addition to gathering their delegates (for example, in conjunction with a Shuttle launch), there might be a teleconference to include their memberships.

(3) An artists' and writers' tour of space opportunities. Artists, dramatists, and film and television producers would be invited to visit key NASA installations and projects to examine the possibilities for collaboration on media projects about space themes, especially those dealing with human migration and communities on the high frontier.

An Artists' and Writers' Tour of Space Opportunities

Robert McCall, NASA-commissioned artist, touches up the middle of a giant mural at the Johnson Space Center's Teague Auditorium. That mural is seen in the background as tourists consider the lunar module test article. Perhaps other artists and writers, including film and video producers, could tour NASA installations to get content for their visualizations of life on the "high frontier." Indeed, Dennis Davidson, art director for the LaJolla summer study and this publication, has made such a tour of the Johnson Space Center with his colleagues in the International Association of Astronomical Artists.

(4) A global space congress on the future of humankind in space, possibly under the auspices of the United Nations or an appropriate international agency. The International Space Year 1992 might be a good opportunity to focus papers and discussions on the kind of space culture we wish to create on the high frontier and whether a global space agency should be formed by the end of this century.

We assume that the proceedings of all the above events would be recorded and published for wider distribution, especially by satellite video.

Institutional

In order to widen institutional support beyond space scientists and engineers, these steps might be considered to enlist professionals and academics in the process of planning space communities:

(1) A university presidents' conference might be held to announce new NASA strategies to strengthen the synergy between the agency and the academic community. For example, as a replacement for the summer study approach, NASA might provide grants for specific research it needs to have undertaken on space technology, management, culture, health, and community development. The purpose of this new grant or contract program would be to involve more academic disciplines, such as behavioral and health sciences, in space planning and to foster doctoral level studies and publications that focus on space systems and communities as well as on space technology. Schools of education and human services, for example, might be asked to analyze curriculum changes related to space age developments.

(2) NASA should also reach out to international and national trade associations and professional societies to involve them in space planning. They could be encouraged to conduct conferences, field trips, and even action research on the applications of their fields to space development. For example, medical organizations could examine space health technology and needs.

Similarly, architectural and construction firms, hotel groups, and travel agents could undertake studies of space tourism. Teachers' organizations might focus on space studies for elementary and secondary schools. With imagination, whole new constituencies could be created in this manner, ranging from law to dentistry.

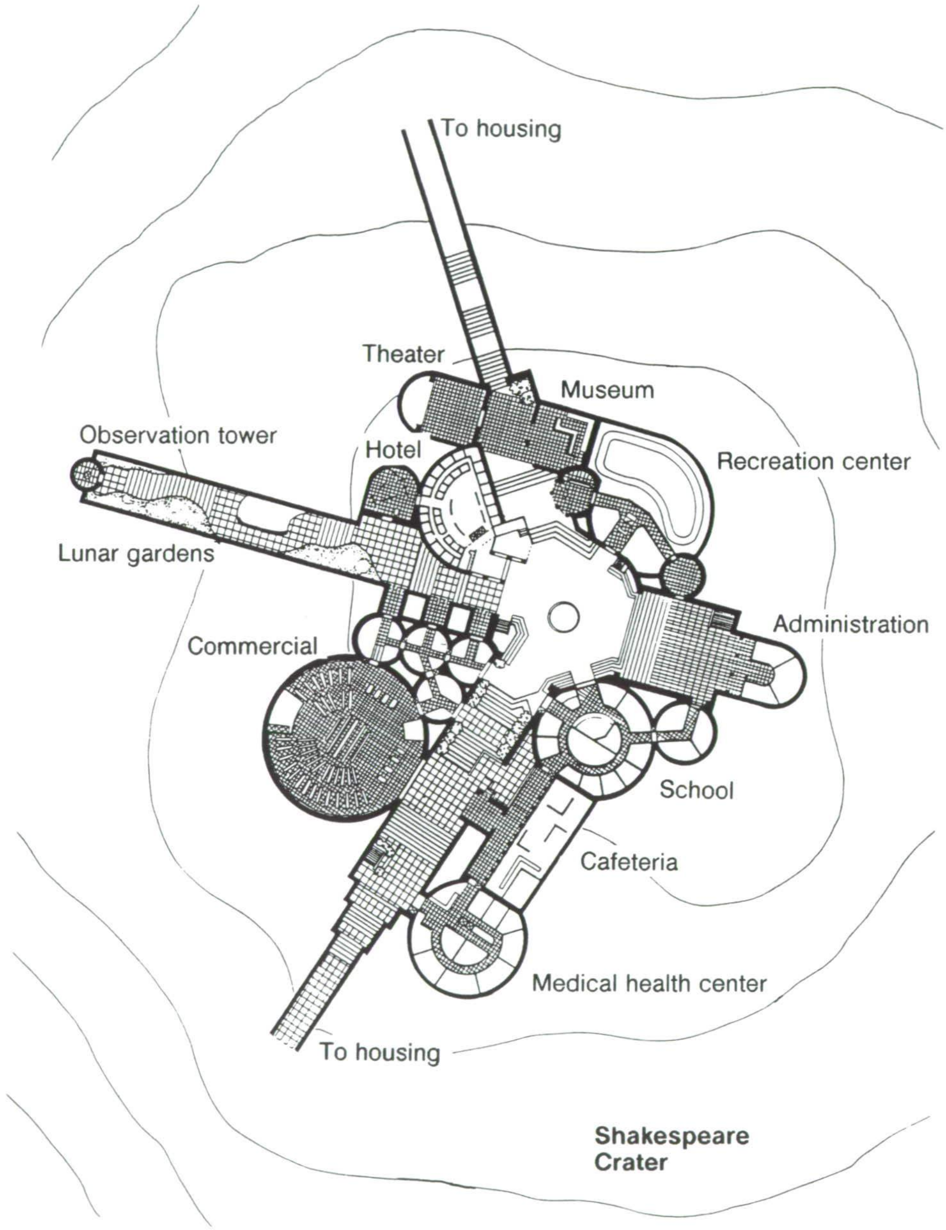
Action Research on Space Health Technology

Skylab astronaut Joseph P. Kerwin, M.D., serves as a test subject for the Lower Body Negative Pressure Experiment. Astronaut Paul J. Weitz, Skylab 2 pilot and experiment monitor, assists with the blood pressure cuff while Kerwin is in the lower body negative pressure device. The purpose of the experiment, which measures blood pressure, heart rate, the heart's electrical activity, body temperature, leg volume changes, and body weight as well as the pressure produced by the device, is to determine cardiovascular adaptation during a mission in weightlessness, to predict the degree of orthostatic intolerance to be expected upon return to Earth's gravity, and to estimate the ameliorative effect of the device. Such action research is supported by health experts and technology producers on the ground.

Artemis, a Senior Architectural Design Project

The hub of a lunar settlement is laid out in Shakespeare Crater. Vera Rodriguez designed this part of a 21st century community for 3000 inhabitants. She and five other students (Carol Haywood, Ruby Macias, Jorge Maldonado, Larry Ratcliff, and Kerry Steen) in the architecture program at the University of Texas at San Antonio researched, developed, and designed the lunar community as a senior design project under the direction of Dr. Richard Tangum. They were assisted in their research by NASA employees at the Johnson Space Center.

Although designed for the well-being, comfort, and enjoyment of lunar inhabitants, many facilities, such as the observation tower, museum (featuring the history of the lunar settlement), library (in the center of the school), and theater would be of interest to visitors staying in the 100-room hotel, which is expected to be one of the largest profit-making parts of the lunar establishment.



Space Studies

A teacher helps students try on space helmets at an exhibit at the Johnson Space Center. Teacher organizations might be involved in the planning of space communities, thereby enlarging NASA's constituency beyond scientists and engineers. Indeed, Pat Sumi, a teacher in the Gifted and Talented Program of the San Diego Unified School District, involved herself in the 1984 summer study of space resources.

International

To build on those results of the foregoing efforts that have international dimensions, NASA should seek specific joint endeavor agreements with counterpart space agencies and their governments in Japan, Europe, the U.S.S.R., and such Third World countries as China and India. Regional economic associations or multinational corporations (some of which are headquartered in the Third World) might prove suitable for such partnerships. To proceed with this globalization of the space program might require some changes within NASA, such as

(1) Creating in NASA headquarters a structure for this purpose with representation in all NASA centers

(2) Recruiting and training specialists with cross-cultural negotiation and communication skills who can effectively manage such international projects

(3) Identifying ventures in which the complexity of the technology or financing makes an international partner desirable

Managerial

To meet the challenge of a postindustrial society and work culture, NASA needs to plan change in its structure, organizational models, and management policies. We recommend that a task force be established to examine the matters of organizational renewal and development of a metaindustrial work culture. Examples of the issues that might be addressed by this group, with the counsel of external consultants, are

(1) Modernizing and decentralizing operational centers and mission control

(2) Developing a macromanagement approach to large-scale programs, such as building a space station or a lunar base

(3) Fostering a more autonomous, innovative, and entrepreneurial spirit or culture within NASA

Thus can NASA and its management transform itself!

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Space Migrations: Anthropology and the Humanization of Space*

Ben R. Finney

Abstract

Because of its broad evolutionary perspective and its focus on both technology and culture, anthropology offers a unique view of why we are going into space and what leaving Earth will mean for humanity. In addition, anthropology could help in the humanization of space through (1) overcoming sociocultural barriers to working and living in space, (2) designing societies appropriate for permanent space settlement, (3) promoting understanding among differentiated branches of humankind scattered through space, (4) deciphering the cultural systems of any extraterrestrial civilizations contacted.

Space is being humanized. We are learning to live and work in orbit; the era of the actual settlement of the Moon, Mars, and other portions of our solar system seems almost at hand; and talk of eventually migrating to other star systems is growing. My task here is to consider what role the discipline of anthropology might play in understanding and in facilitating this process of humanizing space.[1]

At first glance, anthropology might not seem to have much to contribute to such a highly technical and futuristic enterprise as expanding into space. For example, a recent NASA publication entitled *Social Sciences and Space Exploration* includes chapters on economics, history, international relations and law, philosophy, political science, psychology, sociology, and future studies, but not on anthropology (Cheston, Chafer, and Chafer 1984). That omission is perhaps understandable, because anthropologists have typically focused on the long past of humanity rather than on its future and, when they have studied living peoples, they have usually worked with small tribal or peasant groups rather than with large industrial societies. Yet, despite this seeming fascination with the archaic and the small-scale, the perspective of anthropology applied to space can help us comprehend the human implications of leaving Earth and can facilitate that process.

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[1]A separate paper could be devoted to how remote sensing from space is being used by anthropologists to search for buried or otherwise obscured archaeological sites (see "NASA . . ." 1985), to survey land use patterns of living peoples, and even to track reconstructed voyaging canoes as they are being sailed over the Pacific navigated by Polynesian non-instrument methods (Finney et al. 1986).

NASA Transformed

In 1975 the official symbol of the National Aeronautics and Space Administration changed from the insignia on the left to the logo on the right. Though many NASA employees feel affection for the old "meatball" and its symbolism (and the official seal of the agency still bears a resemblance to it), even the most conservative can recognize in the new "worm" a positive change of image. The serif type and boundedness of the old circular symbol have changed to the uniform lines of the new, more open symbol and the vertical thrust of its uncrossed A's. This new image represents a streamlined purposefulness in NASA, an organization in the vertical business of launching space enterprises.

Many of the participants in the 1984 summer study at LaJolla advocated more than symbolic renewal for NASA, to energize the organization as it moves out into the solar system.

An Anthropological Vision

First, and most important, anthropology offers a perspective on humankind that extends back some five million years to the appearance of the first hominids, but it does not end with the evolution of modern human beings and the development of the current high-technology society. Anthropology can help us think about where we are going as well as where we have been. From the perspective of anthropology, we can view our species as an exploring, colonizing animal which has learned to develop the technology to migrate to, and flourish in, environments for which we are not biologically adapted (Finney and Jones 1985). This process began when our distant ancestors developed those first tools for hunting and gathering (see fig. 1), and there is no end in sight. Settling the Moon, Mars, or even more distant bodies represents an extension of our terrestrial behavior, not a departure from it. The technology of space travel, artificial biospheres, and the like may be immensely more complicated than anything heretofore developed on Earth. But, in voyaging into space and attempting to live there, we are doing what comes naturally to us as an expansionary, technological species.

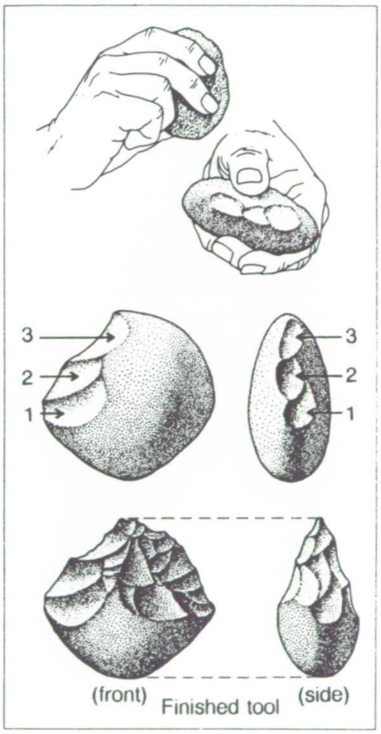

Figure 1

The Beginnings of Technology

Through the development of technology, our distant ancestors were able to spread out of East Africa over the entire globe and to thrive in harsh environments for which we, as basically hairless, tropical animals, are not biologically adapted. The invention of the shaped chopping tool some two million years ago was a major benchmark in this process of technological development. By hitting one rock against another so as to chip off a series of flakes, one can make a crude tool to use in many tasks, such as slicing meat, working hides, and shaping wood and bone into new tools.

Artist: Biruta Akerbergs

Taken from Jolly and Plog 1986, p. 275. Reproduced with permission of McGraw-Hill, Inc.

Yet, settling in space will be a revolutionary act, because leaving Earth to colonize new worlds will change humankind utterly and irreversibly. Anthropologists focus on technological revolutions and their social consequences. The original technological revolution, that of tool-making, made us human. The agricultural revolution led to the development of villages, cities, and civilization. The industrial revolution and more recent developments have fostered the current global economy and society. Now, this same anthropological perspective tells us that the space revolution is inevitably leading humanity into an entirely new and uncharted social realm.

Cultural Analysis

Speculation about revolutionary developments is not, however, immediately relevant to a most pressing question about human adaptation to space: How can groups of people live and work together without psychological impairment or the breakdown of social order in the space stations, lunar bases, and Mars expeditions now being planned? Psychological and social problems in space living constitute, as both Soviet and American space veterans attest (Bluth 1981, Carr 1981), major barriers to be overcome in the humanization of space.

Coping with isolation from Earth, family, and friends and with the cramped confines of a space module or station has been enough of a challenge for carefully selected and highly trained spacefarers of the U.S.S.R. and the U.S.A. As those cosmonauts who have been "pushing the endurance envelope" the farthest attest, staying longer and longer in space provokes severe psychological strain (Bluth 1981; Grigoriev, Kozerenko, and Myasnikov 1985; Oberg 1985, p. 21). Now life in space is becoming even more complicated as "guest cosmonauts" from many nations join Soviet and American crews; as women join men; and as physicians, physicists, engineers, and other specialists routinely work alongside traditional cosmonauts and astronauts of the "right stuff" (see fig. 2). How will all these different kinds of people get along in the space stations of the next decade and the lunar bases and martian outposts which are to follow? What measures can be taken which would reduce stress and make it easier for heterogeneous groups of people to work efficiently and safely and to live together amicably for months or even years in these space habitats?

Figure 2

Space Shuttle Mission 51D, Crewed by K. J. "Bo" Bobko, Dave Griggs, Don Williams, Charlie Walker, Rhea Seddon, E. J. "Jake" Garn, and Jeff Hoffman

Space crews are becoming larger and more heterogeneous. Where once space was virtually the sole preserve of military test pilots from just two of Earth's nations, now women, "guest cosmonauts" from a wide range of countries, and physicians, scientists, engineers, and other specialists routinely join traditional astronauts and cosmonauts in space flight.

This trend can be seen in many of the Space Shuttle crews. In this case, Commander Karol J. "Bo" Bobko (Colonel, USAF) and Pilot Don E. Williams (Captain, USN) were joined in their flight, April 12-19, 1985, by Mission Specialists S. David Griggs (another test pilot, with an M.S. in administration), Jeffrey A. Hoffman (Ph.D., astrophysics), and M. Rhea Seddon (M.D.) and Payload Specialists Charles D Walker, representing McDonnell Douglas Corporation, and E. J. "Jake" Garn, representing the U.S. Senate.

In the coming era of international space stations, and one day on lunar bases and missions to Mars, a major challenge will be how to structure crew relations so that men and women of many nations, cultures, and occupational specialties can live and work together synergistically in space.

Among social scientists it has been primarily the psychologists (Helmreich 1983), with a few jurists, sociologists, and political scientists joining in, who have tried to address these problems of space living. However, inasmuch as among the diverse lot of people who call themselves anthropologists there are those who are intensely interested in interpersonal relations and small group behavior, it should not be surprising that anthropologists might also be attracted to work in this field. Interestingly, some recent recruits come from maritime anthropology, where they have worked on the dynamics of small-boat fishing crews.

These and other anthropologists interested in space can bring to the field a degree of "hands-on" experience in working with "real" small groups—be they fishing crews, Antarctic scientists (see fig. 3), or hunting and gathering bands (see fig. 4). And they bring a tradition of nonintrusive ethnographic observation and description, which might usefully supplement the more clinical and experimental approaches used by psychologists and other social science researchers. Beyond this, moreover, anthropologists can bring a needed cultural perspective to this pioneering phase of space living.

Figure 3

American Station at the South Pole

This station provides one of the closest analogs we have on Earth to a rudimentary base on another planet, in terms of both living conditions and dependence on supplies from outside. The station consists of several buildings—laboratories, service structures, and habitation modules—within a geodesic dome approximately 100 meters in diameter. The South Pole station is continuously inhabited. Crewmembers arrive and depart by air during the summer, but during the long Antarctic winter the dozen or so scientists and support staff live completely isolated from the rest of the world—almost as though they actually were on the Moon.

While the occupants can venture outside with protective clothing ("space suits") during the winter, they are mostly dependent on the shelter provided by the geodesic dome and the buildings within the dome, much as they would be at a Moon or Mars base. Most of the supplies must be brought in by air, but some use is made of local resources. Local ice is used for water, and, of course, local oxygen is used for breathing and as an oxidizer for combustion, including operation of internal combustion engines.

Photo: Michael E. Zolensky

It is through the concept of "culture" that anthropology has made perhaps its greatest contribution to the formal understanding of human life. In this context, anthropologists mean by *culture* those patterns of beliefs, practices, and institutions shared by a particular ethnic population, a profession, a religion, or another grouping. This concept has diffused beyond the social sciences and, in the United States, has become a common tool for thinking about problems within our multicultural society. It has even crossed the threshold into big business and government agencies such as NASA. One can now read books extolling the "culture" of this or that successful corporation, and I have heard NASA managers explain differences between the Johnson Space Center and other NASA centers as being "cultural" in nature. Here I wish to suggest two specific areas in which this cultural perspective of anthropology could be useful: (1) in addressing the problems of cross-cultural relations among heterogeneous space crews and societies and (2) in the application of cultural resources to develop models for space living.

Figure 4

Agta Men Burning Hair and Dirt From the Skin of a Wild Pig

Here, watched by helpers and children in front of a residential lean-to at Disabungan, Icabela, the Philippines, an Agta man performs the first step in the butchering of a wild pig. He burns the hair and outer skin, which he will then scrape off. After this, the hunter will cut the pig into shares to be distributed among the band members, and sometimes offered for sale to loggers, farmers, and fishermen who have moved into the area.

Before the invention of agriculture, all of our ancestors lived by gathering wild plant food, hunting wild animals, and fishing. The Agta are representative of the few hunter-gatherer groups still found in the humid tropics of Southeast Asia, Central Africa, and South America. The Agta live in small bands of from 15 to 30 family members along the coast and in the mountains of eastern Luzon Island in the Philippines. They hunt wild pig, deer, and monkey, and they also fish, gather wild plant foods, and plant small gardens of root crops, rice, or maize.

Photo: P. Bion Griffin

Guest Astronauts and Cosmonauts

Foreign Payload Specialists on the Space Shuttle

Ulf Merbold, West Germany, Spacelab 1, November 28-December 8, 1983

Marc Garneau, Canada, Canadian Experiment (CANEX), October 5-13, 1984

Patrick Baudry, France, Echocardiograph Experiment and Postural Experiment, and Sultan Salman Abdelazize Al-Saud, Saudi Arabia, Arabsat-A, June 17-24, 1985

Reinhard Furrer and Ernst Messerschmid, West Germany, and Wubbo Ockels, the Netherlands, Spacelab 4, October 30-November 6, 1985

Rodolfo Neri Vela, Mexico, Morelos Experiments, November 26-December 3, 1985

*Cosmonauts From Outside the Soviet Union**

Vladimir Remek, Czechoslovakia, 1978

Miroslaw Hermaszewski, Poland, 1978

Sigmund Jaehn, East Germany, 1978

Georgiy Ivanov, Bulgaria, 1979

Bertalan Farkas, Hungary, 1980

Pham Tuan, North Vietnam, 1980

Arnaldo Tamayo, Cuba, 1980

Jugderdemidyan Gurragcha, Mongolia, 1981

Dumitru Prunariu, Romania, 1981

Jean-Loup Chrétien, France, 1982 and 1988

Rakesh Sharma, India, 1984

Muhammed Faris, Syria, 1987

Aleksandr Aleksandrov, Bulgaria, 1988

Abdul Ahad Mohmand, Afghanistan, 1988

**List compiled by James E. Oberg, space researcher and author.*

Cross-Cultural Relations

First, consider the issue of cross-cultural personal relations on international space missions. Space is no longer an arena for just two nations. More and more citizens from a growing number of countries are joining their Soviet and American colleagues in space (see list). If this trend continues, it would be easy to imagine a time when crews aboard permanent space stations or the inhabitants of a lunar base would in effect form miniature multicultural societies.

It could be argued that the highly trained and motivated persons who would participate in such future missions would share a common high-technology space culture that would submerge local cultural differences and any problems that might arise from these. That might describe some future situation wherein crewmembers grow up in a common space culture and thereby share common experiences, expectations, and values. However, as long as crewmembers are born and reared in diverse terrestrial cultures, we cannot ignore cultural differences and their potential for generating problems during international missions.

Cultural misunderstandings, stemming from a difference in interpretation of a command or comment or from a clash in behavioral styles, might be deemed trivial and passed over in a terrestrial setting. But they could become greatly magnified on a hazardous mission where people must put up with one another in cramped quarters (see fig. 5) for months, or perhaps even years, at a time. The Soviets, who have had the most experience with international spacefaring, have admitted to cultural difficulties—even though their guests may speak Russian and share a common ideology with their hosts. As Vladimir Remek, a guest cosmonaut from Czechoslovakia, puts it, unique cultural "mental features" can "disrupt the harmony among crew members" (Bluth 1981, p. 34).

ORIGINAL PAGE
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Figure 5

Cramped Quarters

Cosmonauts Valeriy N. Kubasov and Aleksey A. Leonov are seen in the Soyuz orbital module during the joint U.S.A.-U.S.S.R. Apollo-Soyuz Test Project docking in Earth orbit. This photograph was taken by one of the three American astronauts on the mission—Thomas P. Stafford, crew commander; Donald K. Slayton, docking module pilot; or Vance D. Brand, command module pilot. The American and Soviet spacecraft were joined together in space for 47 hours, July 17-19, 1975.

The 47-hour ASTP rendezvous was a success both technologically and culturally, but the cramped quarters of the Soyuz spacecraft [the Apollo spacecraft was equally cramped (see the photo on p. 12)] and the differences in national styles demonstrate the potential for cultural clashes on longer missions with mixed crews.

One prerequisite for group harmony is good interpersonal communication. Basic to that communication is what the anthropological linguist Edward Hall calls the "silent language" of facial expression, gesture, body posture, and interpersonal spacing (Hall 1959). Members of the same culture tend not to perceive how much is communicated nonverbally, because their shared ways of gesturing and moving their bodies may be so culturally ingrained as to be virtually unconscious. They can therefore be greatly taken aback when confronted with members of another culture who gesture or use their bodies differently. Americans, for example, commonly experience a bewildering sense of discomfort when conversing with Middle Easterners, who habitually stand closer to their conversational partner than the American norm. Conversely, Middle Easterners may interpret Americans' greater conversational distance as a sign of coldness or dislike. Take conversational distance and all the other elements of the "silent language," mix well with an international crew in a crowded space habitat (especially one located in a microgravity environment, where facial expressions are made even more difficult to read because of the puffiness of the face from fluid pooling in the head), and you have a recipe for cultural misunderstanding.[2]

Cultural Resources

Cultural factors should not, however, be viewed solely in terms of impediments to successful space living, for they may also constitute valuable human resources to be tapped in adapting to space. In addition to seeking to promote cultural harmony among heterogeneous space crews, we might also seek out, from the multitude of cultural traditions among the Earth's societies, those practices and institutions which could best promote harmonious and productive life in space.

As an example, consider interpersonal problems in a space habitat. J. Henry Glazer, an attorney who has pioneered the study of "astrolaw," warns against exporting to space communities the adversarial approach to dispute resolution based on "medieval systems of courtroom combat" (Glazer 1985, p. 16). In small space habitats, where people

[2]For another perspective on cross-cultural relations in space, see Tanner (1985).

cannot escape from one another but must work out ways of interacting peacefully and productively, adversarial proceedings would irritate an already sensitive social field. And how could the winners and losers of bitter courtroom battles live and work with each other afterwards?

One obvious suggestion is that systems which are designed to detect interpersonal problems early and head them off through mediation should be considered for space living. Glazer, for example, calls for a new kind of legal specialist—not an adversarial advocate, but someone who settles disputes on behalf of the interests of all spacefarers on a mission. He draws his model from the *Tabula de Amalfa*, the maritime code of the once powerful Mediterranean naval power of Amalfi. Their code provided for a "consul" who sailed aboard each merchant vessel with the power to adjudicate differences between master, crew, and others on board (Glazer 1985, pp. 26-27; Twiss 1876, p. 11). In addition to looking to this and perhaps other maritime analogs, it is tempting to suggest that, with an eye to the more distant future of large space settlements, we also examine major contemporary societies in which harmony and cooperation is stressed. The example of Japan, with its low crime rate and relative paucity of lawyers, comes to mind—although its utility as a model for international efforts may be limited in that Japan is such an ethnically homogeneous society (Krauss, Rohlen, and Steinhoff 1984; Vogel 1979).[3]

New Cultures, New Societies

Once we have learned how to live together amicably in space and to work safely and efficiently there, once we have developed ways of avoiding the health problems of ionizing radiation, microgravity, and other hazards of nonterrestrial environments, and once we have learned how to grow food in space and to produce air, water, and other necessities there, then humankind can actually settle space, not just sojourn there. New cultures and new societies will then evolve as people seek to adapt to a variety of space environments.

[3]See Schwartz (1985) for a comprehensive analysis of the utility of various institutional responses to colonizing opportunities made by migrant farmers from a variety of world cultures.

This process of building new cultures and societies will undoubtedly contain many surprises. Yet, all the resultant sociocultural systems must provide the basic prerequisites for human existence if they are to be successful. Here is where the seeming disadvantage of the anthropologist's penchant for studying small communities may actually prove advantageous.

The sine qua non of anthropological experience is a long and intense period of field work in a small community, during which the investigator attempts to obtain a holistic understanding of the group (see fig. 6). For example, I once spent a year living on a small island in the middle of the Pacific with only 200 inhabitants, during which time I learned the language, became well acquainted with every individual and his or her position in the community, and gathered data on everything from fishing and house building to marriage and religion. Because of this holistic experience of studying a small, relatively self-sufficient community and trying to figure out all its parts and how they fit together, I find most discussions of space settlement curiously incomplete. Typically, they go to great lengths to explain how habitats will be built on a planetary surface or in space, how food will be grown in these habitats, and how the community will earn its way by mining or manufacturing some valuable product; then they skip on to few details about domestic architecture, local government, and the like.

Figure 6

a. Building a Canoe in Polynesia

Men of Anuta Island rough out the hull of an outrigger fishing canoe. This Polynesian community, located on a tiny volcanic island off the eastern end of the Solomon Islands, well away from regular shipping routes, has a population of less than 100 people. Its small size and relative isolation makes Anuta an intriguing community for thinking about life in a small settlement on the Moon or elsewhere in our solar system.

Photo: Richard Feinberg

b. Thatching a Roof in Polynesia

A communal working group thatches a roof on the island of Nukuria, a Polynesian atoll located in the Bismarck Archipelago near New Guinea. In this atoll community of some 200 inhabitants, people work cooperatively on such chores as roof thatching, much as early American farmers used to help each other out with barn-building "bees." The isolation, small size, and relative self-sufficiency of such island communities allows the anthropologist studying them to gain a holistic perspective on all facets of life from birth to death. This holistic perspective in turn may enable anthropologists to foresee critical human elements in future space settlements that planners who are inexperienced in the functioning of small, relatively self-contained communities may ignore.

Photo: Barbara Moir

Among the crucial elements of human life omitted, or glossed over, in these futuristic projections is the most basic one for the survival of any society: reproduction. How mating, the control of birth, and then the rearing of children are to be arranged is seldom even mentioned in discussions of space settlement.[4] Yet, if our ventures in space were limited to communities of nonreproducing adults whose number would have to be constantly replenished with recruits from Earth, we could hardly expand very far into space.

Of course, it could be argued that no great attention will be required in this area—that people will carry into space whatever reproductive practices are current in their earthside societies. But, would that mean a high percentage of single-parent households and low birth rates? A distinguished demographer, whom Eric Jones and I invited to a conference on space settlement, explained his lack of professional interest in the subject by saying that he really did not think there would be much population expansion into space. He argued that the nations most likely to establish space settlements are those which have passed through the demographic transition from high to low population growth and that, furthermore, the highly educated, technology-oriented people who would be the ones to colonize space are those inclined to have the fewest children, perhaps not even enough for replacement of the population.

A population's demographic past is not necessarily a reliable predictor of its future. however, as we should have learned after the surprise of the post-World War II baby boom in the United States (Wachter 1985, pp. 122-123). It seems obvious that, when people perceive that it is to their advantage to have many children, they will do so. For example, Birdsell (1985) has documented how, in three separate cases of the colonization of virgin islands by small groups, the population doubled within a single generation. Figure 7 (Birdsell 1957) graphs the population growth on Pitcairn Island from 1790 to 1856. Unless radiation hazards, low gravity, or some other aspect of the nonterrestrial environment constitutes an insuperable obstacle to our breeding in space, there is every reason for optimism about the possibility of population expansion in space.

[4]But times may be changing. NASA psychologist Yvonne Clearwater (1985, p. 43) has recently raised the issue of sexual intimacy in space, and law professor Jan Costello (1984) has just published an inquiry into the issues of family law in space.

Nonetheless, the export into space of some current features of mature industrial societies, such as the high cost of educating children, the desire of both parents to have full-time professional careers, and the lack of institutions to aid in child rearing, would certainly act to slow expansion. Space settlers interested in expanding their populations should structure community values and services in such a way that people would want to have more than one or two children and would be able to afford to in terms of both time and money. An anthropological perspective could aid space settlers in constructing a socioeconomic environment for promoting population growth; first, by helping them to break out of the assumption that the way things are currently done in mature industrial societies represents the apex of human development; and, second, by informing them of the wide range of reproductive practices employed by the multitudes of human societies, past and present.

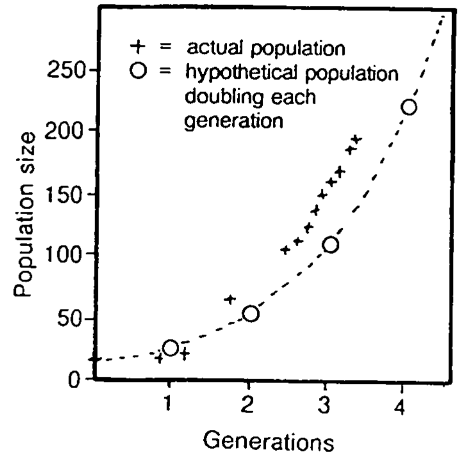

Figure 7

Population Growth on Pitcairn Island, 1790-1856

If physical conditions can be made favorable for human existence on other planets or in orbiting space habitats, the experience of small groups of people colonizing uninhabited islands suggests that our spacefaring descendants may expand rapidly—until checked by resource limitations. In 1790 six English mutineers from the H.M.S. Bounty, *eight or nine Tahitian women, and several Tahitian men settled on the tiny, uninhabited island of Pitcairn. Despite genocidal and fratricidal quarrels among the Tahitian men and the mutineers, the population more than doubled each generation, reaching almost 200 in 1856, when lack of food and water forced evacuation of the island.*

Adapted from Birdsell 1957.

Some of the practices from our remote past might even be relevant to our future in space. Suppose, for example, that the harshness of the airless, radiation-intensive environments of space, combined with the economics of constructing safe human habitats, dictates that the first space settlements would have to be small, containing well under a hundred people (Oberg 1985, p. 183). Pioneering space colonies might therefore be in the size range of the hunting and gathering bands in which most of our ancestors lived before the discovery of agriculture and the consequent rise of urbanization. If so, space settlers might face some of the same problems relating to reproduction as did their distant predecessors: the genetic dangers of inbreeding, random imbalances in the sex ratio of children born into the group, and what might be called the "kibbutz effect," wherein children reared close together are not markedly attracted to one another upon coming of age (Spiro 1965, pp. 347-349).

Our predecessors could avoid these problems with one simple institution: the practice of exogamy, whereby youths had to marry someone from outside their natal group, thus enlarging the effective breeding community to encompass hundreds of persons, not just a few dozen. Of course, it could be argued that sperm and egg banks, in vitro fertilization, and even in vitro gestation and genetic engineering may be so advanced by the era of space colonization that there would be no need for exogamy. Yet, marrying outside of one's group can bring benefits that may not be obtainable by other than social means.

Exogamy can promote social solidarity by binding together otherwise separate and scattered communities into a network of units which, in effect, exchange marriageable youths. Although the Australian aborigines, for example, lived scattered over their desert continent in small bands averaging 25 men, women, and children, they were linked together in tribes of some 500 people (Birdsell 1979). This larger tribal community was more than a breeding unit. At appointed times, the members of all the bands would gather together to arrange marriages, conduct rituals, and enjoy the fellowship of friends and relatives from other bands. Just as this tribal community provided the aborigines with a needed wider social group, so might a space age confederation of intermarrying space colonies help their pioneering inhabitants fight the loneliness of space (Jones and Finney 1983).

Of course, a space age exogamy system would probably not replicate all the features of its archaic predecessors. Take, for example, the custom of female bride exchange, whereby the marriageable young women were sent to other groups, which in turn supplied brides for the young men who remained at home. Space age young women would surely object, on the grounds of gender equality, to any rule that required that they leave home to marry, while their brothers could stay. Conversely, adventuresome young men might not relish the idea that they must remain at home and import their brides. More than likely, if the ethos of space communities is explicitly expansionistic, then both males and females will vie for the opportunity to leave their natal community and, taking a mate from another established community, go off to found a new colony.

Role of Anthropology

Assuming that someday it becomes widely accepted that anthropological insights and findings could help us understand human expansion into space and aid in that process, the question arises: How are those insights and findings to be applied and who applies them?

The suggestion that a corps of anthropologists be recruited to facilitate smooth cross-cultural relations in international space stations, to design appropriate institutions for permanent space communities, and to forecast the biocultural impact of moving into space might bring approval from my space-oriented colleagues and hope to many a new anthropology graduate trying to find a job in today's tight academic market. However, I would not advocate that anthropologists be elevated to the status of elite experts in planning human expansion into space. Anthropology is not an exact science in the sense that it can make accurate and precise predictions. Anthropological gurus of space expansion would hardly be infallible prophets or unerring social engineers. Instead, I foresee a more modest role for anthropologists as students of space expansion and advisors in that process.

The ideal recipients of that advice would not be some earthside planners charged with designing the social structure of space stations, lunar bases, and even more futuristic endeavors. Ultimately, the people who should receive the most appropriate advice on anthropological matters are those who will actually live and work in space. Call it self-design, home rule, or just plain independence, the underlying premise is the same: those who will actually reside in space stations, planetary outposts, and the first true space colonies should have a crucial role in the initial design of their particular community and, above all, in the inevitable modifications to that design which would arise through experience. In this light, the burden of space anthropologists—some of whom must do field work in space if they are to live up to their calling—would be to come up with relevant insights, findings, and recommendations derived from both terrestrial societies and groups in space and to communicate these to the spacefarers and colonists.

Two centuries ago a group of gentlemen farmers, lawyers, and politicians, faced with the task of constructing a viable nation out of a disparate collection of ex-colonies, came up with a remarkable document, the Constitution of the United States, which set out a form of democratic government that has since proved most successful (see fig. 8). This document, and the resultant form of government, was the product of a concerted design process based on a comparative study of forms of government instituted at different times and places through history, a study undertaken not by outside experts but by those who had to live in the resultant nation. I look forward to many such occurrences in space when the space settlers themselves—not earthside planners or even a space-based planning elite—sit down, sift through the accumulated human experience, and come up with principles for the design of new societies adapted to their needs in space. Here is where the anthropological record—from both Earth and space—and the principles derived therefrom could make a major contribution to the humanization of space.

Figure 8

Framing a Constitution for a New Nation, Philadelphia 1787

In framing the Constitution of the United States, a group of gentleman farmers, lawyers, and politicians, representing a tenuous union of ex-colonies, drew upon models of political organization provided by ancient Greece and Rome and other earlier states, as well as the writings of Enlightenment philosophers, to construct a totally new form of government suited to the needs and aspirations of Europeans transplanted to a New World.

Some time in the future, when and if spacefaring and spacedwelling technology is sufficiently developed, similar scenes may be reenacted as space settlers—drawing on the accumulated experience of terrestrial polities and inspired by space age philosophers—set out to devise new forms of government adapted to the needs and aspirations of developing nations in space.

Artist: Howard Chandler Christy

If We Are Not Alone

While the solar system appears to be the sole province of humankind, we do not know whether we are alone in the galaxy. Should we have company and should we or our descendants make contact with extraterrestrials, then anthropology might have a new role in space. The experience of anthropologists in trying to bridge cultural gulfs could be applied to the immense task of comprehending an extraterrestrial civilization.

Ten years ago a group of anthropologists and other social scientists published a book entitled *Cultures Beyond Earth* (Maruyama and Harkins 1975) exploring just such an "extraterrestrial anthropology." They assumed actual physical contact, via interstellar travel, between us and the extraterrestrials. To scientists engaged in the Search for Extraterrestrial Intelligence (SETI), however, the prospect of actually making physical contact is extremely remote. They argue that the physical problems and great cost of interstellar travel, as opposed to the relative ease and economy of radio communication, plus the great value that advanced civilizations would place on information, as opposed to physical experience, mean that contact will be made via the electromagnetic spectrum, not in person (Morrison, Billingham, and Wolfe 1977). Although the view that interstellar travel will never occur is arguable, a case can be made that, even if physical contact eventually takes place, speed-of-light radio communication would precede it (see fig. 9). Hence, the question is "What role could anthropology play in cultural analysis at a distance?"

Figure 9

Radio Telescope at Arecibo, Puerto Rico

The world's largest radio telescope (305 meters in diameter), at Arecibo in Puerto Rico, is operated by the National Astronomy and Ionosphere Center at Cornell University under contract to the National Science Foundation. The Arecibo telescope will soon be used by NASA in a systematic search for radio transmissions from other star systems in the galaxy, transmissions that might indicate the presence of extraterrestrial intelligence.

The physics of the formation of the universe suggest that in the millions of galaxies with their billions of stars planetary systems may be the rule rather than the exception. The chemistry of the development of life on Earth, together with the discovery of organic molecules even in the depths of interstellar space, leads many scientists to consider the development of life on other planets as very likely.

The SETI program will search for life that has achieved intelligence and developed technology by looking in the quietest band of the electromagnetic spectrum (1000 to 100 000 MHz) for radio signals that may have leaked or been beamed from such highly developed civilizations on other planets. NASA's Ames Research Center will conduct a targeted search of stars like our Sun using the largest radio telescopes, including the one at Arecibo. The Jet Propulsion Laboratory will conduct a complementary survey of the other 99 percent of the sky, using the 34-meter-diameter telescopes in NASA's Deep Space Network. The SETI program is developing a spectrum analyzer that will sample millions of frequency channels looking for narrowband emissions that may be continuous or pulsed signals. Should such deliberately created signals be found, anthropologists will find ample work in interpreting the signaling culture to the receiving one and vice versa.

With extraterrestrial contact rephrased in terms of radio communication only, it might seem that anthropologists and their skills would have little or no role to play in this grand intellectual venture—at least in terms of the common SETI scenario. That scenario envisages the reception of a purposefully transmitted signal containing some mathematical truth, physical constant, or other noncultural knowledge that would presumably be universally shared among intelligent species scientifically advanced enough to engage in radio communication. The next step in this scenario would be to build upon this universal knowledge to develop a common logical code or language—either through a patient and clever tutelage directed by the transmitting civilization or through a lengthy dialog across the gulf of however many light years might be involved (Freudenthal 1960). Signal processing experts, mathematicians, cognitive scientists, and linguists would seem the obvious specialists to participate in this radio contact process, not anthropologists.

However, it would be a mistake to assume that once a common code was shared, the rest of the task would be easy. Philip Morrison, whose joint paper with Giuseppe Cocconi (Cocconi and Morrison 1959) stimulated the SETI effort, wisely points out that a "complex signal will contain not mainly science and mathematics but mostly what we would call art and history" (Morrison 1973, p. 338). To decode such a signal would be difficult enough. To interpret the cultural material would call for an immense effort. Just think of the scholarship involved in deciphering the hieroglyphs and in reconstructing ancient Egyptian culture, even though the ancient Egyptians are of the same species as their modern investigators and in part culturally ancestral to them and even though they left the Rosetta Stone! (See figure 10.) Interpreting an extraterrestrial culture would be a never-ending task, which would generate a whole new scholarly industry, calling for the talents of specialists from all disciplines, especially anthropology. Anthropologists concerned about the disappearance of independent cultural entities on Earth should be among SETI's most ardent supporters. If the search is successful, anthropologists will have more than enough to do—for millennia to come.

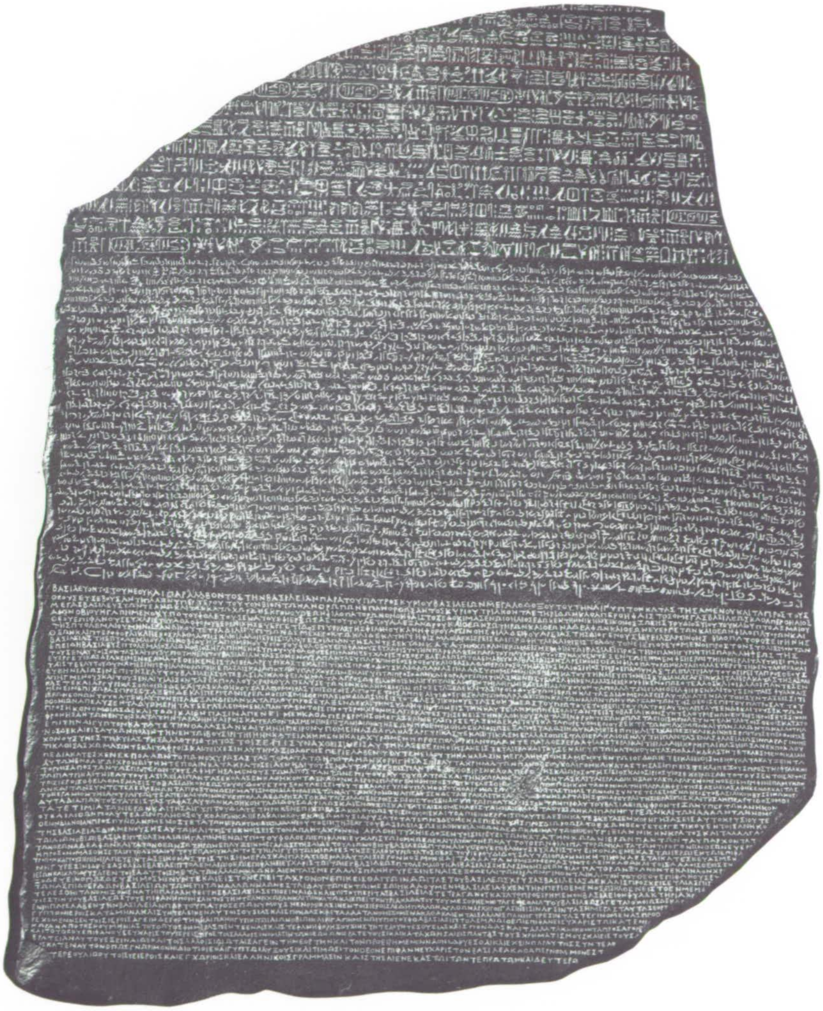

Figure 10

The Rosetta Stone

A slab of black basalt, rescued from demolition in A.D. 1799 by a squad of Napoleon's troops in an Egyptian village called Rosetta, and containing a decree passed by a council of priests in 196 B.C., provided the key to the decipherment of Egyptian hieroglyphics.

The officer in charge of the squad, Lt. Pierre François Xavier Bouchard, is credited with having realized almost at once that the three inscriptions on the stone were versions of the same text. The content of the decree was soon known from a translation of the Greek capital letters in the bottom inscription. But the nature of the other two scripts—Egyptian hieroglyphics in the top portion and the cursive Egyptian script called demotic *which appears in the middle—was not fully understood until 1822. Neither form of Egyptian writing had been used for 1,370 years.*

A blocking misconception was the idea that, while hieroglyphics were merely pictorial, demotic was strictly phonetic. An English scientist turned linguist, Thomas Young, broke through this block and provided the link that the two Egyptian scripts were related through an intermediary script called hieratic. *His translation of the demotic and the work of W. J. Bankes on the phonetic nature of royal names led French scholar Jean François Champollion to the conclusion that both Egyptian scripts on the Rosetta Stone contained symbolic and alphabetic elements. His knowledge of Coptic, the language of the Christian descendants of the ancient Egyptians, which was written in a sort of cross between Greek and demotic, helped him to finally decipher the Egyptian language in its most ancient script—hieroglyphics.*

And, of course, with knowledge of the language came a great increase in knowledge of the culture of the ancient Egyptians.

Explanation taken from Carol Andrews, 1981, "The Rosetta Stone," published by the British Museum.

Photograph reproduced by courtesy of the Trustees of the British Museum.

Even if we are the only intelligent species in the galaxy, or at least our corner of it, we might not be alone for long. If our own technology for settling space really works and enables some of our descendants to disperse throughout the solar system, a dramatic cultural rediversification of humankind would occur as the widely scattered colonies develop (through cultural drift or conscious choice) new ways of living. Then, if adventurous citizens of the solar system one day migrate to other star systems, their separation into small, self-contained breeding communities light years from their neighbors would virtually ensure biological speciation (Finney and Jones 1985). Earth-descended, though increasingly disparate, cultures and species would then be faced with the problem of understanding each other. Within such a galaxy of differentiating intelligent life forms, "astroanthropology" would be an essential tool for comprehending and relating to others beyond one's own cultural and biological experience.

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The Influence of Culture on Space Developments

Philip R. Harris

For a quarter of this 20th century, humankind has been successfully extending its presence into space. The landing of men on the Moon in 1969 during the Apollo 11 mission broke our perceptual blinders—we were no longer earthbound as our ancestors had thought for centuries. Perhaps the real home of the human species lies on the high frontier. Just as the application of fire and tools changed our primitive forebears, so space technology and its accomplishments force modern men and women to change their image of our species. We now are free to explore and use the universe to improve the quality of human existence. Our new self-concept as "Earth people" may energize global efforts toward space development. The technological achievements of NASA and other national space agencies, along with private-sector space undertakings, contribute mightily toward the actualization of our human potential. The exploration and exploitation of space resources are altering our human culture here on Earth.

Such vision is necessary to put the endeavors of space scientists and technologists into a larger context. During the past 25 years, the feats of people in the National Aeronautics and Space Administration and the allied aerospace industry have advanced human culture. The next steps of space technology into the 21st century will transform that culture.

Culture—A Coping Strategy

Culture is a unique human invention. Our species created it to increase our ability to cope with the environment, to facilitate daily living. Thus, consciously and unconsciously, groups transmit it to following generations. The concept of culture provides a useful tool for understanding human behavior and its relationship to a particular physical environment.

Human beings created culture, or their social environment, in the form of practices, customs, and traditions for survival and development. Culture is the lifestyle that a particular group of people passes along to their descendants. Often in the process, awareness of the origin of contributions to this fund of wisdom is lost. Subsequent generations are conditioned to accept these "truths" about accepted behavior in a society; norms, values, ethics, and taboos evolve. Culture is communicable knowledge which is both learned and unlearned, which is both overt and covert in practice, of which we may have either conscious or unconscious understanding. On this planet, human culture has been remarkable for its diversity, so that those who would operate successfully in an international arena have to learn skills for dealing effectively with cultural differences. The point is that culture is a powerful influence on human behavior as people adapt to unusual circumstances (Harris and Moran 1987).

The program manager for long-range studies at NASA's Office of Space Flight has listed some of the unusual circumstances on the high frontier that might influence the creation of a space culture: (1) weightlessness; (2) easy gravity control; (3) absence of atmosphere (unlimited high vacuum); (4) a comprehensive overview of the Earth's surface and atmosphere (for communication, observation, power transmission, etc.); (5) isolation from the Earth's biosphere (for hazardous processes); (6) an infinite natural reservoir for disposal of wastes and safe storage of radioactive products; (7) freely available light, heat, and power; (8) super-cold temperatures (infinite heat sink); (9) open areas for storage and structures; (10) a variety of non-diffuse (directed) types of radiation; (11) a magnetic field; (12) nonterrestrial raw materials; (13) absence of many Earth hazards (storms, floods, earthquakes, volcanoes, lightning, unpredictable temperatures and humidity, corrosion, pollution, etc.); (14) a potentially enjoyable, healthful, and stimulating environment for humans (Von Puttkamer 1985).

As the director of the California Space Institute, James R. Arnold, reminded us in a Los Angeles *Times* editorial (November 17, 1983), "Space is out there waiting for us to try out new ideas." In his view, the space station and other space bases to follow will give humans the time and place to learn, to experiment, to work, and even to play. In fact, the Soviets have already begun to do these things on their Mir space station. The formation of space culture has been under way now for over 25 years, and it is progressing rapidly.

Until now, only a handful of humans have actually lived in space. Whether Americans or Russians or their allies, these space pioneers were usually from a somewhat homogeneous background. Until the decade of the 80s, they came from subcultures like test pilots or the military and were mostly male. But, if we project to the next 25 years, it is obvious that the population in space will be increasingly multicultural and heterogeneous. Both Soviet and

American space flights, for example now include representatives of "allied" countries—cosmonauts or astronauts from "foreign" cultures. Just as on Earth there are human experiences that cut across most cultures, it would appear that living in space will become such a "cultural universal."

As we slowly extend our presence up there and establish human space communities in ever increasing numbers, there will be an urgent need for *cultural synergy*, be it on a space station or at a lunar base. Such synergy optimizes the differences between people, fosters cooperation, and directs energy toward goals and problem-solving in collaboration with others (Moran and Harris 1982). The very complexity of transporting people into space has stimulated the development of matrix or team management in the space program. Similarly, the creation of space habitats and colonies in a zero- or low-gravity environment will require synergistic strategies of leadership.

Current research in evolution indicates that harsh environments often result in innovation by species. The pattern of the past reveals that creatures are better at inventing and surviving when challenged by a difficult environment than they are when not challenged (Harrison and Connors 1984). The big jumps in species development seem to occur under such circumstances. Perhaps this will be true of the human race as we shift our attention from Earth-based to space-based resources. As the Apollo missions demonstrated, the very size, scope, and complexity of a space undertaking may be the catalyst for unleashing our potential and raising our culture to a new level. This may be the first time in human history that people can consciously design the kind of culture they wish to create in an alien environment slated for exploration and exploitation. The movement of people from their home planet to the "high ground" will transform both our culture and the human person. The editors of *Interstellar Migration and the Human Experience* remind us that "Migration into space may be a revolutionary step for humanity, but it is one that represents a continuity with our past" (Finney and Jones 1985).

Space planners can benefit immensely by utilizing the data base and insights of behavioral scientists (Connors, Harrison, and Akins 1985). Cultural anthropologists, for instance, offer a variety of approaches to cultural analysis. One method is called a systems analysis; here "systems" refers to an ordered assemblage of parts which form a whole. Thus, in planning space communities, one might utilize eight or more systems, such as illustrated in figure 11. That is, the new space culture can be studied in terms of systems that are used to indicate relationships—for association, or social grouping; for economic and political purposes; for education and training; for health and recreation; for leadership and guidance (this last being the transcendent or philosophical system around which the space community might be organized). In *Living Systems* (1978), James Grier Miller has proposed a master paradigm for integration of both biological and social systems. Dr. Miller is currently engaged in research to apply his eight-level conceptualization of twenty subsystems to analysis of the cultural needs of future space communities (see his paper in this volume).

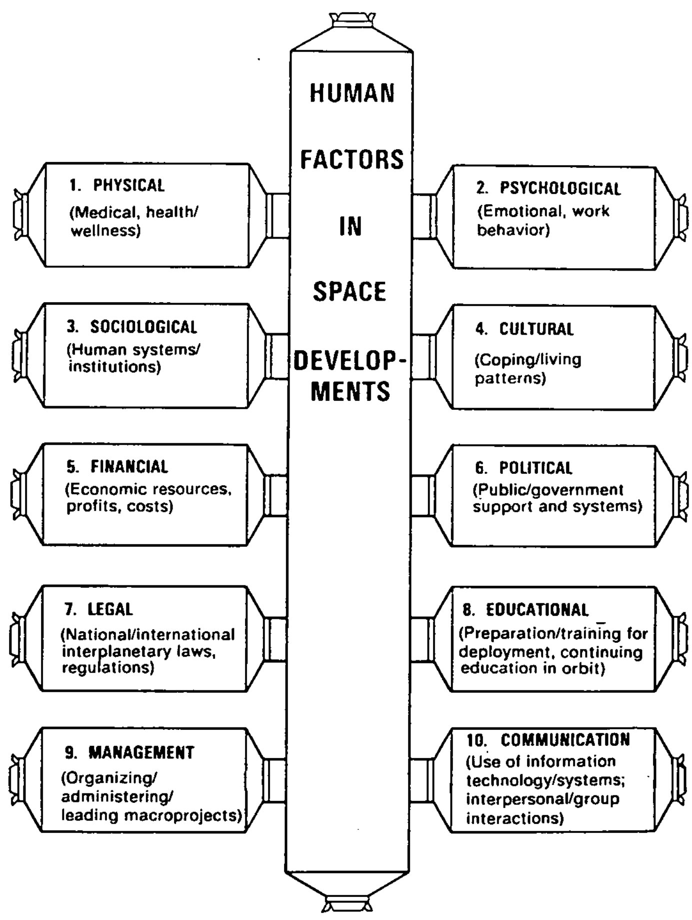

Figure 11

Systems for Analysis of a New Space Culture

Another way of preparing for a new cultural experience is by examining typical characteristics of culture. Some of these for a space community might be the following:

(1) Sense of self

(2) Communication

(3) Dress

(4) Food

(5) Time consciousness

(6) Relationships

(7) Values

(8) Beliefs

(9) Mental processes

(10) Work habits

These ten classes offer a simple model not only for assessing an existing culture but also for planning a new one, such as a culture in space. Although there are other characteristics for cultural analysis (such as rewards), analysis of the listed characteristics would be sufficient to prepare for a startup space community, such as that of the crew at a space station or a lunar outpost.

Because culture is so multifaceted and pervasive in human behavior, we cannot simply impose one form of Earth culture on a space community. Nor can space technologists continue to ignore the implications of culture (Hall 1985). If the space population is to be increased and broadened, so should the composition of space planners and decision-makers (as happened in miniature with the multidisciplinary group of participants at the 1984 NASA summer study at the California Space Institute.)

Organizational Culture in NASA and the Aerospace Industry

Culture has already unconsciously affected our future in space through the organizational cultures of the chief developers of space technology. A distinctive culture has emerged in the past 25 years within NASA itself, and this in turn has influenced the corporate cultures of NASA's principal contractors. NASA has been an atypical government agency that has been innovative in both technology and management, as well as in its relations with contractors (Harris 1985).

When NASA was established as a civilian Government entity in 1958, it inherited cultural biases from the several organizations from which it was derived. It acquired many of the traditional characteristics of Federal public administration, being subject to the constraints of Civil Service regulations, annual budget battles, congressional and lobby pressures, and changing public opinion (Levine 1982). Since it was chartered to be mainly a research and development organization, NASA was dominated by the subcultures of the scientific, technological, and engineering fields. Its interface with the military and its astronaut personnel from the Armed Forces provided another stream of cultural influence. The introduction of the German rocket specialists under Wernher von Braun provided further cultural input, as have numerous academics and their universities, beginning with Robert Goddard of Clarke University and coming right down to participants in the latest NASA summer study on the campus of the University of California, San Diego.

Currently, the organizational culture of NASA is being altered by its interactions with other national space agencies, such as those of Japan and Europe, and even by its successful cooperation with the Soviets in the Apollo/Soyuz mission. To broaden its constituency further, NASA is attempting to reach out to nonaerospace business and involve companies in space industrialization; to expand its cooperative efforts with other Government departments, from weather and transportation to commerce and defense; to engage in joint endeavors with national academies and associations, such as the American Institute of Aeronautics and Astronautics (AIAA). The ongoing history of NASA manifests continuing alterations of its culture from crises (e.g., the *Challenger* disaster) and reactions (e.g., congressional investigations) and new inputs from Presidential commissions (e.g., the Rogers Commission report, 1986).

Just as groups of people develop national or macrocultures, so too do human institutions develop organizational or microcultures. NASA as an organization is a collection of humans who have set for this system objectives, missions, expectations, obligations, and roles. It has a unique culture which is influencing the course of space development. The NASA culture begins by setting organizational boundaries and powerfully affects the morale, performance, and productivity of its employees. Eventually, this influence spreads to contractors and suppliers. For example, as NASA began to plan for its next 25 years, Administrator James Beggs circulated a statement of goals and objectives to administrators and center directors. This statement from the first item enunciated demonstrates a future trend in NASA culture:

GOAL: Provide our people a creative environment and the best of facilities, support services, and management support so they can perform with excellence NASA's research, development, mission, and operational responsibilities.

(*Government Executive*, October 1983, p. 5)

To analyze this NASA culture, one can take the ten characteristics listed in the previous section or one can use a diagnostic instrument (see "Organizational Culture Survey Instrument," appendix A in Harris 1983). Perhaps figure 12 best illustrates the possible dimensions of this NASA culture.

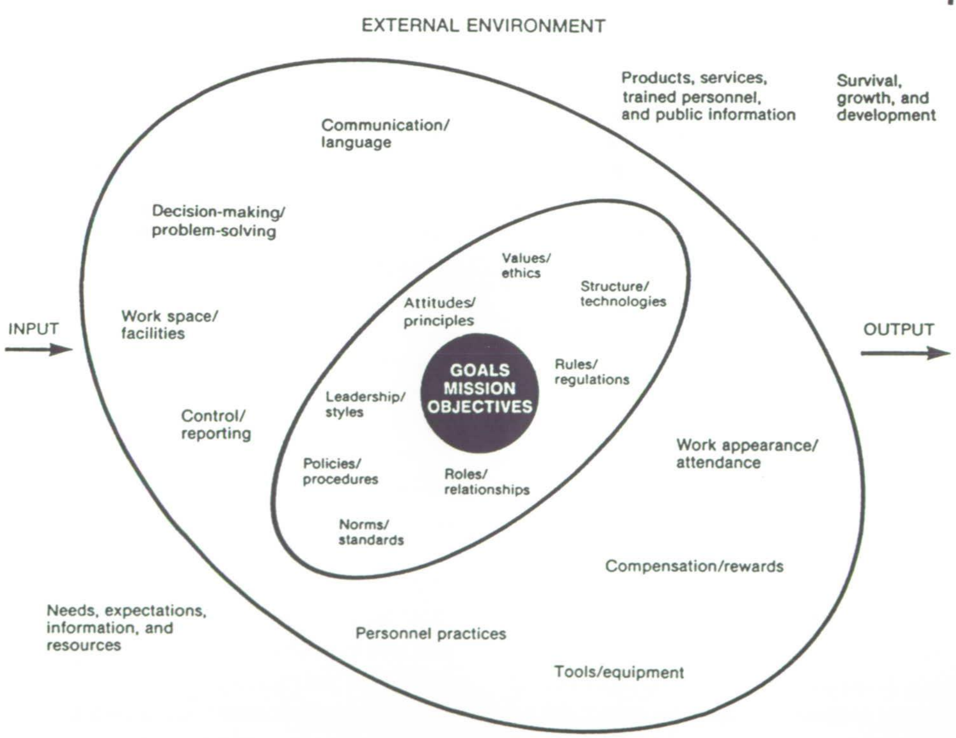

Figure 12

Aspects of NASA's Organizational Culture

The fact that NASA successfully completed its Apollo lunar missions would seem to indicate that its organizational culture was adequate. Since then, budget cuts, loss of talented personnel, and the *Challenger* accident have pointed up the need for cultural renewal. In 1986, as a result of the report of The Presidential Commission on the Space Shuttle Challenger Accident, reorganization got under way following the appointment, once again, of James C. Fletcher as NASA Administrator.

The issue of concern now is whether the agency's cultural focus will enable NASA to provide global leadership in the peaceful and commercial development of space. As NASA struggles with "organization shock," external forces demand that priority be given to military and scientific missions, leaving commercial satellite launchings and industrialization to the private sector. Other international space agencies—in Europe, Japan, and even the Third World—compete with NASA in launch capability. Confusion reigns over replacement of the fourth orbiter, development of alternative launch capability, and space station plans, so that NASA is an organization in profound transition, requiring transformational leadership (Tichy and Devanna 1986). This is especially true if NASA is to implement the vision outlined by the National Commission on Space (1986) in its bold report, *Pioneering the Space Frontier*.

As an example of the way NASA culture affects its space planning and management, consider the well-documented fact that the agency is leery of the behavioral sciences (Harrison 1986, Hall 1985, Douglas 1984). Since the organization is dominated by a technical mindset, it is uncomfortable with social scientists and their potential contributions. And yet the agency culture changes, as witnessed by the publication of the June 1988 report of the NASA Life Sciences Strategic Planning Study Committee, entitled *Exploring the Living Universe: A Strategy for Space Life Sciences*, and by requests for increased spending on the behavioral sciences in the FY89 budget.

As human presence in space is expanded with long-duration missions, NASA planners will have to confront issues of interpersonal and group living which until recently they avoided (Connors, Harrison, and Akins 1985). In interviews by flight surgeon Douglas (1984) with astronauts, the latter expressed regrets that they and their families did not benefit more from the services of psychiatrists and psychologists, particularly with reference to group dynamics training. Oberg (1985) reveals that, on the other hand, in the culture of their space program, the Soviets are more prone to utilize such specialists. In fact, that author quotes the Soviet head of space biomedicine, Dr. Oleg Gazenko, as stating that the limitations to human living in space are not physical but psychological (p. 25); Oberg also notes that Svetlana Savitskaya, the second woman in space, suggested that a psychologist be included on long-duration flights to observe firsthand the individual stress and group dynamics (p. 32).

My purpose here is simply to bring to the reader's consciousness the reality that NASA does have a culture and that that culture pervades its decisions, plans, operations, and activities. One might even take the chapter headings of the volume *Corporate Cultures* and use them to assess NASA's values, heroes, rites and rituals, communications, and tribes (Deal and Kennedy 1982).

As reported in a variety of contemporary management books, from the one just mentioned to *In Search of Excellence*, research supports the conclusion that excellent organizations have strong functional cultures. Since its founding, NASA surely has created its share of space leaders, legends, myths, beliefs, symbols, visions, and goals—the stuff of meaningful organizational cultures. But, as Peters and Waterman reminded us,

> In the very institutions in which culture is so dominant, the highest levels of true autonomy occur. The culture regulates rigorously the few variables that do count, and provides meaning. But within those qualitative values (and in almost all other dimensions), people are encouraged to stick out, to innovate.
>
> (Peters and Waterman 1982)

Thus, if NASA is to provide the world with the technological springboard into the 21st century, these questions are in order:

(1) Does NASA now have the necessary innovative and entrepreneurial culture to provide leadership for its own renewal and the enormous human expansion into space? Or is it trapped inside both bureaucratic and technical cultures that inhibit its contributions to the next stage of space development?

(2) Has NASA adequately redefined and projected its present organizational image and purpose to its own personnel, the Congress, and the public at large? Or is it suffering again (as it did after three astronauts were killed in the Apollo capsule fire) from an identity crisis and a dysfunctional culture?

As NASA moves beyond its institutional beginnings into the next stage of organizational development, maturation would seem to require transformation. Perhaps the present structure is no longer suitable for this growth process and it needs to become a more autonomous agency. (Does the Tennessee Valley Authority provide a model for this structural change?) Perhaps it should be part of a global space agency that represents both public and private space interests—first in the free-enterprise nations and someday even in the Communist bloc. Perhaps NASA needs to enter into new relationships and ventures with contractors, whether in the aerospace industry or in other multinational industries.

It was encouraging to know that the 1984 NASA administrator advocated decentralization in the organization, putting operational responsibility at the center level. However, in 1986 the trend was being reversed with demand for strong headquarters management and inauguration of a new technical management information system. To meet the space challenges of the future, NASA would do well to consider planned changes in its own organizational culture. Technological, economic, political, and social changes by 2010 will demand such adjustments, and many present organizational structures, roles, operations, and arrangements (such as a centralized mission control) will be obsolete.

Emergence of a New Space Culture

The habitation of Skylab, Spacelab, Salyut, and Mir by a few dozen humans is the precedent not only for space station life but also for space culture. Whether astronauts or cosmonauts, they were humans learning to cope with a new environment marked by a lack of gravity. For most, it appears to have been an enjoyable experience, despite minor inconveniences caused by space sickness or excessive demands from experiment controllers on the ground. Whether inside or outside the space suits and capsules, these people learned to adapt and they proved that human life in space is possible, even practical. These innovators simply transported into space the macroculture of the country that sponsored their space voyage. The U.S. astronauts reflected American culture, while their Soviet counterparts carried Russian culture into these prototypes of future space communities.

In the decade of the 1990s, the duration of missions and the number of humans in space will increase as more permanent types of space stations are constructed in orbit and expanded in size. Perhaps the Americans will name these initial space communities after their space pioneers and heroes, like Goddard, Von Braun, and Armstrong; while the Russians may name theirs after space luminaries like Tsiolkovsky, Korolev, and Gagarin. Then the real challenge of creating a new space culture will get under way. A major human activity of the 21st century will be the building of space communities. Already, Rep. George Brown (D–Calif.) has a bill pending before the U.S. Congress that would authorize NASA to provide leadership in space settlements.

The issue for consideration now is whether this process will be planned or unplanned. In the United States, for example, there exists a whole body of literature and research in cultural anthropology that could be most useful in the design of a space culture. Anthropologists are beginning to probe this new reality and to look for insights their field can contribute (see Finney's paper in this volume). Will NASA, for example, use the nation's anthropologists in the planning of a lunar base? If the human composition of that enterprise is to be multicultural, as is likely, will the agency call on international experts in cross-cultural psychology and anthropology? Perhaps NASA should join with its colleagues in the Japanese and European space agencies in sponsoring a summer study of behavioral scientists to address matters related to the emerging space culture.

Space gives us an opportunity to establish a living laboratory to promote peaceful international relations. For example, suppose the sponsors of a particular space station or base were to have as a goal the establishment of a synergistic society on the high frontier. Anthropologist Ruth Benedict and psychologist Abraham Maslow have already provided us with a glimpse of human behavior under such circumstances. Imagine a space community in which the cultural norms supported collaboration and cooperation rather than excessive individualism and competition. Consider space colonists who are selected because they demonstrate high synergy—that is, because they are nonaggressive and seek what is mutually advantageous; they encourage both individual and group development; they operate on a win/win philosophy, or aim for group success; they share and work together for the common good. Such considerations take on special relevance in light of proposals for a joint U.S.A./U.S.S.R. mission to Mars. A space culture that espouses synergy might have a better chance for survival and development than one that did not. We should have learned something from the debacle of Fort Raleigh in 1594, the first "lost colony" of our English forebears.

Since culture formation seemingly occurs in response to the physical environment, consider briefly the situation faced by those seeking to establish the first permanent community on the Moon, a base from which we can explore other planets in the universe. It is a remote, alien environment. The long-term inhabitants would have to adapt their culture to cope with isolation, for they would be a quarter of a million miles away from home, family, and friends on Earth. The physical realities of life on the Moon would force its inhabitants to adapt their earthbound culture (Pitts 1985). Remember, the Moon lacks atmosphere, there is no weather there, and there are various kinds of radiation which require protective cover.

Back in 1969, astronauts Armstrong and Aldrin confirmed that the lunar surface was firm and could support massive weight. During the last visit to the Moon, Apollo 17, the first professional scientist on these missions, Dr. Harrison Schmitt, conducted geological studies, so we now have some idea of the composition of this body. But there is much we still do not know about the Moon, such as the nature of its poles and whether any of its craters were formed volcanically.

Before the turn of this century, it would seem advisable for NASA to follow a Soviet lead and undertake automated missions to gather lunar data if we are to plan adequately for the new space culture on the Moon's surface. At NASA's Johnson Space Center, scientists have a scheme for cultural expansion which begins with precursor exploration in a 1990-92 timeframe (Duke, Mendell, and Roberts 1985). It would require new technology development to exploit lunar resources and define the site for a research outpost and lunar base. The first two phases of site development would rely on automated and cybernated systems. In the third phase, permanent human occupancy by a small group of "astrotechnicians" is projected; then, in the fourth phase, an advanced base with more people would result, possibly by the year 2010.

To illustrate why serious preparations for a Moon base should include studies of space culture by social scientists, let us view figure 13 in the context of a lunar base.

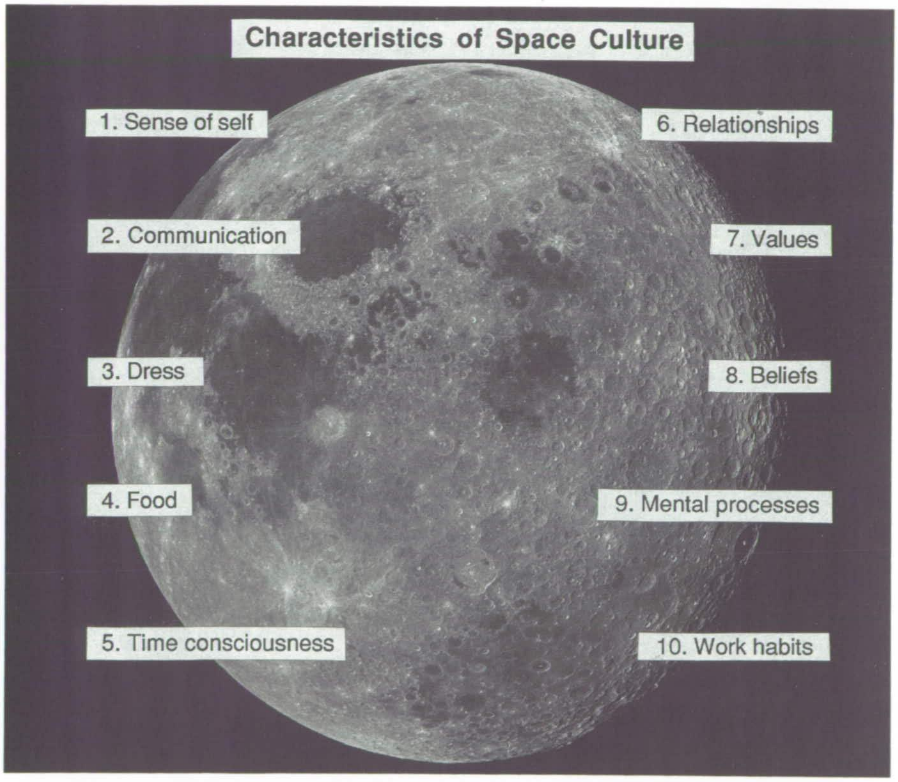

Figure 13

Characteristics of Space Culture

1. Sense of Self

Self-identity and self-acceptance are manifested differently in different cultures. The comfort we feel with ourselves and others, the physical or psychological space we maintain between ourselves and others—these are products of culture. For an international crew on a space station, as an example, there would be differing needs for privacy or personal space. One can speculate as to whether an international community on the Moon should, for the purpose of fostering such comfort, be structured as an open or a closed society. Personally, I would recommend an open, friendly, informal, and supportive community, such as expatriates often maintain among themselves when far away from their mother country. (Though the society of expatriates may be seen as closed to the surrounding society on Earth, such a perspective would be irrelevant in space where humans are alone.)

The space culture to emerge will validate individuals in new ways. First, there are the realities of no atmosphere and 1/6 gravity—certain to lead to interesting adaptations. With so much space and so few people, rugged individuals may develop (like the mountain men on the early Western frontier) or humans may learn to become more interdependent. Just as the American Great Plains affected the perspective of its inhabitants, so will the vast views of the universe affect lunar dwellers. Considering the confined quarters in the early stages, will the first colonists be ambivalent in behavior because of the difference between their sense of interior space and that of exterior space? Also, what happens to lunar colonists when they return to Earth after several years on that other sphere? Having been accustomed to Moon weight, they will on return to Earth feel heavier than lead, and their whole sense of self will require profound readjustment.

2. Communication

Much of our terminology may be inappropriate for the lunar experience. In space, we will need a new vocabulary to replace "up and down" and "day and night." Back in 1957, when German space science professor Hermann Oberth wrote his classic *Man Into Space*, he reminded us that we would have to change our ideas about construction, because "other laws prevail in space and there is no reason why the old architectural rules should be followed." By extension and analogy, our language about construction and indeed most other subjects will have to change in a drastically different environment.

Will there be one official language or several in use? If the first crews and settlers are international in makeup, is English to be preferred or should all be fluent in two languages? (If Americans were to undertake a joint mission to Mars with the Soviets, for instance, then both English and Russian would probably be required.)

Certainly, we can expect extensive use of computers and satellites for communication, but what will be the procedures and the pattern of interactions between humans on the Earth and on the Moon, and how will the means of communication affect the cultural expansion?

3. Dress

Culture is also expressed in garments and adornments. We may or may not want uniforms with mission patches, but lunar conditions will dictate certain types of clothing or space suits. They will have to be designed to serve a variety of purposes from protection to comfort. In 1984, for example, the first female to walk in space, cosmonaut Svetlana Savitskaya, commented that her space suit was not elastic enough and that she had to expend too much energy for each movement (Oberg 1981).

Some scientists have described the Moon as an impossible environment for humans, but so was the Earth for the first living things there—they coped by staying in the sea for the first two billion years! Humans will adapt to lunar conditions which require them to wear life support systems when they leave their protective habitats. That necessity will be incorporated into the new culture, and it will alter behavior from that on Earth. Dr. David Criswell, director of the Consortium for Space and Terrestrial Automation and Robotics (C-STAR), believes that astronauts in space suits are like disabled or handicapped persons, and that space planners could learn much from the field of rehabilitative medicine (1988).

Twenty-first century clothing styles on the home planet may be very much influenced by styles that develop for the lunar surface or for interstellar travel. Explorers and scientists in the Antarctic have tended to grow beards and longer hair. We wonder what lunar dwellers will do. Perhaps they'll shave off all their hair to keep from having to tuck it into their space suits every time they don them.

4. Food

The diet and eating procedures of a group of people set it apart from other groups. We are all aware of NASA's pioneering in food technologies and compositions, so that even our own intake here on Earth has been altered by the astronaut experience. However, because of transportation costs, we will have to cut back on the amount and type of food cargo from Earth and depend on new closed biological systems to provide human sustenance. Hydroponic farming, featuring plants suspended in nets above circulating liquids that provide nutrients, may prove a boon. With traditional foodstuffs at a premium, the new culture may focus on high-quality and high-energy nourishment, thereby affecting the breed of both humans and other animals in space.

Although the lunar cuisine may not be as pleasant as that of the mining camps in the Old West, its preparation, presentation, and eating will surely alter the culture. One certainty is that food packages will not be disposable but rather recyclable. Let us hope habitat planners make up somewhat for the rations and regimen by providing a view of the Earth in the dining and drinking area. Or will there be any views from these modules buried in lunar regolith for protection from radiation?

5. Time Consciousness

The sense of time differs by culture, and yet lunar inhabitants will have to keep in touch with mission control. Will the 24-hour time system prevail on the high frontier? Or will the exact sense of time gradually be replaced by a relative one, like that of traditional farmers who go by sunrise and sunset and seasonal changes?

That particular time sense would of course have a different expression on the lunar surface, where the "day" lasts for 2 weeks and so does the "night." Because the axis of the Moon does not tilt as does the axis of the Earth, the Moon lacks seasons. Will the long periods of darkness and isolation incline the first Moon colonists toward suicide, as NATO has found its soldiers posted in northern countries to be? Will they suffer with manic behavior, as some Swedes do after their annual dark periods? If one needed change, one could move around the Moon from areas of darkness to areas of light. But what will happen to the whole concept of day and year, so much a part of the human heritage?

6. Relationships

Cultures fix human and organizational relationships by age, sex, and degree of kinship, as well as by wealth, power, and wisdom. The first lunar inhabitants are likely to establish relationships on the basis of professionalism or their respective disciplines. They will be scientists and technicians, civilian and military. Theirs will be primarily work or organizational relationships, even if they are of different nationalities. Because the first colonists will be knowledge workers (that is, people who work with information and ideas), there is likely to be comparative social equality among them. Eventually, the founders will gain special status in the community.

The first element to alter the arrangement will be male-female relations. Eventually, this will lead to the first pregnancy on the lunar surface. As more and more people go to the Moon, there will be legal and illegal liaisons and eventually children will be born on the Moon, and someday on Mars. Dr. Angel Colon of Georgetown University Medical School has already anticipated the situation with his research on space pediatrics.* The point is that space will be a whole new ball game in terms of human relationships and a culture will grow in response to such new realities.

New familial arrangements will emerge (Oberg and Oberg 1986). It remains to be seen whether monogamy, polygamy, or polyandry will become the norm in 21st century space communities. If the first lunar colonists are only males, homosexuality may become prevalent; whereas, if mixed groups are sent, then heterosexuality will be the basis for many relationships. Astronaut Michael Collins (1988) proposes that six married couples be selected for any manned mission to Mars.

Should the makeup of the first crew be purely civilian, then we could expect one lifestyle; whereas, if military people are included, then we would expect another lifestyle including rank and protocol. The issue of such relationships will affect governance, housing assignments, and social life.

Another unique feature of space culture will be human-machine relationships. Automation will dominate not only the transportation system but also the exploration and life support processes (Freitas and Gilbreath 1980, Automation and Robotics Panel 1985). Humans may form new attachments to their helpers, especially as designers program more humanlike capabilities and features into these extensions of ourselves. Inventive applications of artificial intelligence on the Moon may not only facilitate functions in lunar communities but also serve as tests of expert systems, which may then be transferred to Earth. Knowledge engineering will accelerate as a result of space development, and space culture will feature teleknowledge (information developed by technical transmission) and telepresence.

*Personal communication.

7. Values

The need system of the space culture will be unique, and out of it will evolve special priorities to ensure survival and development. In time, these priorities will form the value system of the lunar base. As the colonists move up on the hierarchy of needs, their values will change. The resulting value system will in turn influence the norms or standards of the lunar community—that is, acceptable behavior in that situation. It is these mutual premises that will determine whether the colonists are pleased, annoyed, or embarrassed by the conduct of their fellows. Eventually, this process will produce conventions that are passed along to each new group of lunar settlers, so that the preferred practices of privacy, deference, etiquette, and gift-giving will be established.

For example, it is conceivable that these lunar pioneers may ban all talk of Earth accomplishments, happenings, or experience and focus only on what is done on the Moon or in space. They may learn to value the people on the space station, who supply them, more than remote people on the home planet, even when they represent the government. Because of their unusual view of the cosmos and the light/dark situation on the Moon, they may value artists more highly than technicians, for their capacity to express the pioneers' feelings and longings.

At the 1974 Princeton Conference on Space Colonization, Richard Falk examined "New Options for Self-Government in Space Habitats." He proposed four shared commitments that would enhance space living: (1) to the minimization of violence, (2) to economic well-being for all settlers in the habitat, (3) to a guaranteed level of social and political justice, and (4) to the maintenance and improvement of ecological quality (1977). Falk's premise is that this sort of value consensus before settlement would influence recruitment and selection of space personnel, as well as provide an ethical orientation for their training.

8. Beliefs

People's lives, attitudes, and behavior are motivated by spiritual themes and patterns which may take the form of philosophy, religion, or transcendental convictions. If the population of a lunar community is international, the space culture emerging on the Moon might include beliefs from the Earth's religious traditions—primarily Judaism, Christianity, Islam, Hinduism, Buddhism, and even Confucianism. However, since such belief systems are also reflections of new stages in human development, space dwellers may create their own unique form of "cosmic consciousness" that raises the human race to a new level of being and perceives the oneness of the human family. For example, suppose a space colony were developed on the basis of a belief in synergy; the members would then be dedicated to creating a synergistic society through cooperation.

9. Mental Processes

The way people think and learn varies by culture because of different emphasis on brain development and education. Space culture, for instance, may offer humanity a rare opportunity to focus on whole, not split, brain development. Obviously, modern communication technology and satellites will have a primary position in information sharing and knowledge development. For education and training, the first lunar colonists will rely on computers and a data bank, as well as on a variety of modern media alternatives. Self-instructional systems will be widely employed, and all in the group will be expected to share their expertise and competencies with each other as circumstances require.

Assuming that a multicultural community develops, a synergy may emerge between Eastern and Western cultural orientations to learning, so that an integration of logic, conceptualization, abstract thinking, and intuition may evolve. We can anticipate a new reasoning process being created in space, especially with wider applications of artificial intelligence. With the removal of many ground-based blinders and binders, the creative process may be unleashed and human potential actualized.

10. Work Habits

One way of analyzing a culture is to examine how the society produces its goods and services and conducts its economic affairs. The work culture in space will be metaindustrial and will feature the use of high technology. In the beginning, the work will be performed outside using cumbersome space suits to provide life support. Or it will be done by robots, operating automatically or under the manual guidance of humans, who may remain in a protected habitat. On the surface of the Moon, for instance, this work may involve the mining, transportation and distribution, and processing of lunar materials.

Human vocational activity will include the operation and repair of communication satellites, the creation of solar power stations, and the conversion of solar power into microwaves for transmission to Earth and subsequent reconversion to electricity. The first space stations, as well as bases on the Moon, and subsequently on Mars, will involve much construction—using new space materials and designs to build habitats and factories, communication and storage facilities, and other necessary structures.

The early space workers will focus on the transformation of nonterrestrial resources into useful supplies, such as oxygen, water, and cement. The nonterrestrial workers will use zero or low gravity to facilitate their labor, and they will take advantage of the vacuum. All of this work will require extensive use of computers and automation, and the "tin collar worker," or robot, will be a principal ally.

Such unusual work activities will influence the direction of the culture. The roles of knowledge workers and technical workers will probably be enhanced. Since those who get into the first space communities are likely to be highly selected, competence in one's field of expertise and multiskillfulness are norms that will probably emerge. The space culture will reflect these worklife changes in art and artifacts as well as in technology.

The new space enterprises and the culture thus created are a fruitful arena for social science research. Furthermore, these developments will have enormous impact on Earth-based work cultures. Large American corporations, from Fairchild and McDonnell Douglas to General Dynamics and Rockwell, are already gearing up for construction of the $8 billion space station, the staging area for exploration of the rest of the solar system. It may very well develop as a multinational facility for spacefaring peoples—a foretaste of 21st century life and culture.

Space Personnel Deployment System

The movement of large numbers of people from their native country to a foreign one has spurred increasing interest, especially on the part of transnational corporations, in the phenomena of culture shock and reentry shock. When people are rapidly transported from their home culture to a strange environment abroad, they may experience severe disorientation, confusion, and anxiety. Their sense of identity is threatened when they are removed from the comfortable and familiar and thrust into the uncertain and unknown. Such expatriates, particularly overseas managers and technicians who may be away from home for many months or years, go through a transitional experience that may include such phases as growing awareness of differences, rage, introspection, and integration.

Many multinational businesses have relocation services, as well as cross-cultural orientation and training programs, to facilitate acculturation of personnel to the new environment with its changes and challenges. In a previous publication, I have proposed that various aspects of foreign deployment support services be systematized (Harris and Moran 1987). Such an approach could be adapted for Earth people going into space to establish first construction bases and then planned communities. Figure 14 depicts my conception of a space personnel deployment system.

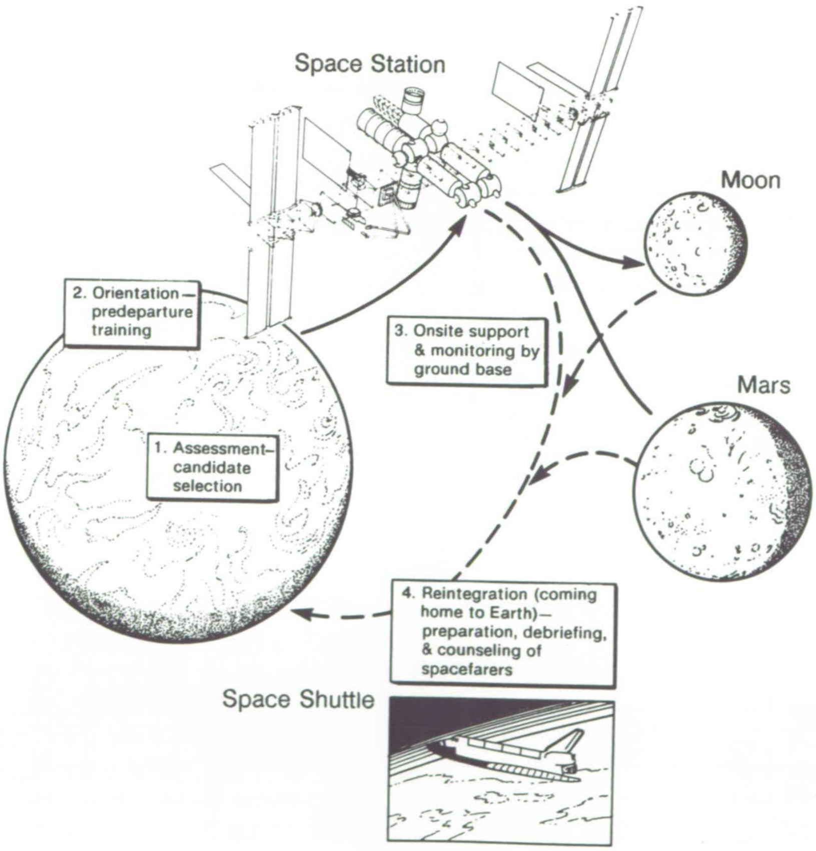

Figure 14

A Space Personnel Deployment System

At the moment, it is unlikely that spacefarers will have to deal with extraterrestrial "foreigners"—but they will have to cope with all the other aspects of adaptation to a new cultural environment. Research by Harrison and Connors (1984) on groups in *exotic environments* is relevant. Their "exotic environments" include polar camps, submarines, offshore oil rigs, space capsules—any isolated and remote living situation. Such experiences can assist in planning life in space stations and settlements.

We can thus prevent or limit the psychological "shock" of isolation, loneliness, and strangeness that humans may experience when living on the high frontier for many months or even years. The following outline of a system for intercultural preparation and evaluation is proposed for further research by NASA. It could avoid or reduce the depression, withdrawal, hostility, paranoia, and other mental health problems that may afflict space travelers, and thus it could contribute to mission success.

1. Assessment

In the next decades of space development, sponsoring organizations should take care in the selection of space settlers, workers, and travelers. Whether the group is a national space agency, an aerospace contractor, a commercial enterprise, a government department, a media company, or a tourist firm, it should be responsible for the spacefarer's well-being, as well as the impact of that person on the space community. Better to screen out potential misfits than to attempt to provide care and rehabilitation in space. The rigorous and defined selection and training used for NASA astronauts may not be the basis for future space deployment; these guidelines would seem advisable as a more diverse space population evolves:

- WHAT—Ascertain the ability of each space candidate to adapt to and deal effectively with the new environment, evaluate both the physiological and the psychological capability of the individual to deal with the difficulties and differences of long space travel and of life in space under constrained conditions, identify proneness to space culture shock and areas for retraining to improve adjustment to space conditions, ascertain needs for skills in human relations and coping.

- WHO—Apply such screening of space travelers and settlers to all who would utilize Government transportation, whether NASA personnel, contract workers, visiting professionals, members of the Armed Forces or Congress, visiting dignitaries from any source, representatives of the media, tourists, or the families who accompany any of these people to a space station or base.

- HOW—Use a variety of means to evaluate suitability for space living, such as psychological interviews, questionnaires, tests, simulations, and group meetings.

- WHY—Seek not only to determine suitability but also to identify those requiring preventive counseling because of their likelihood to experience space culture shock. The aim is to eliminate from space communities, at least in their founding stages, those who would want to return to Earth prematurely, those who would be disruptive influences in a space colony, and those who would simply not be satisfactory for their space assignments. Initially, the cost of transporting people to and from space will demand a careful selection policy and program.

NASA should consider establishing an organizational data bank on human factors to be used in the selection and preparation of spacefarers. Such a data bank might include information from research on personnel living in such exotic environments as submarines or the scientific bases in Antarctica. It might contain information on space habitat conditions and lifestyle, including data on food, medical conditions, responses to weightlessness, and skills required. Eventually, as experience in space living increases, the data bank might include specific cultural information for space stations in orbit, lunar bases, martian bases, and similar locations in space. Space "expatriates" while onsite or upon return to Earth would be asked to contribute insights to this fund of knowledge about life in zero or low gravity. Eventually, such input could be classified by the orbit in which the experience was garnered.

In time, this data bank about space life may become the basis of policy and guidelines for space travel which would be formulated by government agencies, corporations, or other organizational sponsors of people in space. It may someday contribute to practical decisions about such interplanetary matters as laws and insurance, passports and visas, financial compensation and allowances, taxes, security, training, and suitable dress.

In selecting the first space workers for a tour of duty of 12 months or less, practicality may give preference to those healthy and well-balanced persons who (a) have already had astronaut training, (b) come as a happily married couple with complementary competencies, and (c) are committed to long-term living in space.

Undoubtedly, NASA has already assembled a wide range of data about the performance and needs of astronauts in space during the past 25 years. In the next quarter century, we expect that a more heterogeneous population will be going into space. Research should be funded on the dimensions for successful space adaptation. Eventually, a profile, useful for assessment, could be developed of requirements in space for technical competence, resourcefulness, creativity, productivity, adaptability, emotional stability, motivation, risk-taking, interpersonal and communication skills, leadership and growth potential, cultural empathy, and other psychological, as well as physical, attributes.

We should take advantage of this period before the time of mass travel into space to conduct research on and develop means of coping with that alien, sometimes hostile, zero- or reduced-gravity environment. The pioneers who experience space life in the next 25 years can provide insight into the new culture and information on adjusting to it. Their Earth-based sponsors should do everything possible to enhance their well-being and success in space, while learning from them about their experiences aloft.

2. Orientation

The second component in a space deployment system is a combination of self-instruction and training to prepare personnel for life beyond this planet. Oberg (1985) has described the astronauts' training, which offers a basis in this regard. However, with a more diverse population going into space, more generalized training would be needed. The curriculum would depend on the orbit, length of stay, and mission. Some of the training would be designed to develop skills in one's area of expertise, such as space technology or administration. Some of it might be to develop a secondary role to fulfill in the space community, such as food provider or paramedic. All would be expected to complete a basic course in space living that would deal with zero- and low-gravity compensation, life support systems, physical care and exercise, mental health services, and human relations. All would be given orientation to the cultural challenges of space communities and specific information about the cultures of their fellow crewmembers.

The learning program would include human behavior issues like communication, motivation, team-building and synergy, leadership, conflict management and negotiation, and family relations, both with those in space and with those left behind on Earth. Presumably there would be a need for all to learn something about space safety, the robotic and computer systems to be used at the space station or base, and the basic equipment that everybody would be expected to operate, such as an airlock or a rover. Possibly courses in astronomy, space migration, and space community development and systems, as well as in space recreation and constructive use of leisure time, might be among the innovative learning opportunities.

Instruction might include video case studies, simulations, programmed or computerized learning, and questionnaires. The content would draw heavily on information gathered about life in space by both American and Soviet space scientists. Instructors presenting live or media training should include those with experience in space.

There might be international, national, or regional space academies established by the turn of the century for such educational preparation. (The military academy model might be adapted for these new peace academies.) NASA, for example, might consider a location adjacent to the East-West Center near the University of Hawaii, where ample resources would be available. (Such a Pacific Basin site for an international space university was proposed in 1985 by Tetsuo Kondo, a member of the Japanese Diet, and by U.S. Senator Spark Matsunaga, and in 1986 by people addressing the National Commission on Space.) The faculty of a space academy should range from astrophysicists and astrochemists to behavioral scientists and astronauts. The program objectives would be to prepare spacefarers for effectiveness and excellence in their space cultural experience.

In addition to the example of the NASA training program for members of the U.S. astronaut corps, prototype space orientation programs can also be found in the educational offerings of the U.S. Space Camp and the International Space University founded in 1987.

3. Onsite Support and Monitoring

An effective space deployment system should include a third component of support services and monitoring by Earth-based sponsoring organizations. One dimension of this support would include all the food, supplies, equipment, facilities, communication, and transport necessary to maintain a community of humans in space. If we designate this as "physical support," the other dimension to be concerned with is "psychological support." That is, a program onsite at a space station or lunar base which will facilitate integration into the host environment and culture.

Upon arrival at the space location, the newcomer should benefit from an acculturation program, which may include being paired off with a seasoned "buddy," receiving indoctrination briefings, and being presented with media programs that will familiarize the person with the local scene, its dangers and its opportunities. Communication links have to be established so individuals can keep in touch with family and friends at home on Earth. New forms of video/audio recordings may be transmitted by satellite which will keep spacefarers informed of events in their families, hometowns, and organizations. To counteract alienation while boosting morale, Earth-based sponsors might have an information exchange with their representatives in space; it could range from organizational news bulletins to shopping services and training updates.

NASA today physically monitors the vital functions and well-being of its astronauts. Dr. James Grier Miller is planning a computer monitoring system for those on a space station. It is conceivable that organizational sponsors of space expatriates might wish to have a "space wellness program." This could be a more comprehensive approach that furthers the mental or holistic health of the space dwellers. It might include needs adjustment surveys, performance data analysis and reporting, and individual or group counseling. As individual and group data is amassed in an organization's computers, insights will be gained with which to improve the whole deployment system. Special attention should be paid to high-performing spacefarers (Harris 1988). Written records and videotapes of such top performers in space can be helpful in preparing others for the challenge of space living.

Such data will influence on-the-job training, design of space habitats and equipment, programming of recreational and other leisure time, work scheduling, procedures for making assignments and scheduling leave, and devising salary and benefit plans, especially for more hazardous service.

In the startup stages of a space operation, only emergencymedical assistance may be available to space dwellers. But, as the human space community grows and we move beyond frontier living conditions, more extensive physical and psychological assistance should be made available to spacefarers who need it. Problems may arise from the disruption of an individual's circadian rhythm, the effects of the gravity-free environment, the stress of lack of privacy, and the effects of lengthy space stays. There are many human factors related to space living that will have to be addressed by those responsible for deploying people in space, not the least of which is how to develop a viable sense of community with relevant psychological, social, political, and economic ideas.

A whole new infrastructure needs to be built on Earth to support space-based activities properly, including regional bases on this planet that are directly linked to a particular space enterprise. Similarly, an infrastructure has to be created at the space facility where humans will dwell, one that will deal with the needs and aspirations, weaknesses and failings of the species.

4. Reintegration

Until now human missions in space have been counted in minutes, days, weeks, and months. Present planning for the space station by NASA, for instance, calls for six to eight people working a 90-day shift. Current research indicates that humans can stay in space without unacceptable physical deterioration for up to 12 months before being rotated. Obviously, if human space migration is to take place, we must move beyond these constraints. Some have proposed that the first space settlers should be volunteers who commit to space either permanently or for a long time. They argue that the first colonists to the New World came to stay, not to be rotated back to Europe. Others point to the length of sheer travel time for interplanetary missions, such as 2-1/2 years to Mars and back, and discourage any plans for too-quick rotation of space colonists. Visionaries speculate that the human body will eventually adapt to the differences in space life, that a new gene pool and even a new breed may evolve over generations.

Starting with the construction crews and astronauts on the first

NASA space station, we can assume that guidelines will be set for safe lengths of stay. In the initial stages of space base development, we can expect regular reentry of space workers to the Earth's environment. If we are to avoid "reentry shock," the process of preparing people for that transition should begin on the high frontier. Perhaps astronauts who have been to the Moon and back would make the best consultants for designing such programs. Space people will have to readjust both physically and psychologically to the home planet. Their sponsoring organizations should have a plan for facilitating their reintegration into Earth's lifestyle and tempo. Reentry counseling may range from reassignment to occupational activities on this planet to preparations for return to the high frontier. Some will experience "you-can't-go-home-again" syndrome, while others will complain of a variety of traumas and crises upon their return and may even require outplacement from space services or assistance with a divorce. The interplanetary experience may prove to be more profound than cross-cultural experiences here on Earth.

To close the space deployment loop, we should gather and analyze information from returning expatriates. Data gathered through questionnaires, interviews, or group meetings should be computerized. This data should be analyzed to improve the future recruitment, selection, and training of spacefarers and to improve the quality of life in space communities.

San Diego State University professor Arthur Ellis has begun to examine the role of social work in the space age.* As large space colonies are planned, he believes that the human services field can contribute to establishing policies, services, and ethics that will protect and enhance society's human resources in space. Ellis envisions the application of social work methodology to the stress and depression experienced when individuals are separated from their families by space missions or when they must endure long periods together in a space community. The hazards of being human in an alien environment may demand that some form of space psychotherapy be available both on the high frontier and on return to Spaceship Earth.

Conclusion

The human race is in transition from an Earth-based to a space-based culture, and the process of this "passover" may take centuries.

*Personal communication.

> We *Homo sapiens* are by nature wanderers, the inheritors of an exploring and colonizing bent that is deep . . . in our evolutionary past. . . . Whereas technology gives us the capacity to leave Earth, it is the explorer's bent, embedded deep in our biocultural nature, that is leading us to the stars.
>
> (Finney and Jones 1985)

Anthropologist Finney and astrophysicist Jones remind us that it is the species called "wise"—*Homo sapiens*—which evolved biologically and adapted culturally so as to populate and make a home of this planet. These same inclinations and capacities propel humanity into the solar system and may be the catalyst for interstellar migrations. Finney and Jones speculate on an explosive speciation of intelligent life as far as technology, or the limits placed by any competing life forms originating elsewhere, will allow.

The humanization of space, in any event, implies the extension of Earth cultures, both national and organizational, into the universe. It means creating not just new space technologies, methods of transportation, and habitats but a wholly new lifestyle and way of thinking that evolves appropriate societal and economic structures, legal and political systems, art and recreation, as well as suitable life support. Early in the next century our extraterrestrial pioneers may produce the first space-born generation that is not psychologically dependent upon Earth. In time, these high frontier dwellers may raise a different type of human.

The "creeping" begins with the Shuttle that takes us 300 miles or so to a space station, a platform for assembling the world's best scientists and engineers in low Earth orbit. The "walking" begins when we can regularly, economically, and safely extend our presence 23 000 miles above the Earth's surface to geosynchronous Earth orbit. There or at bases on the Moon and Mars we will mature and step into the universe and a new state of being.

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Future Space Development Scenarios: Environmental Considerations

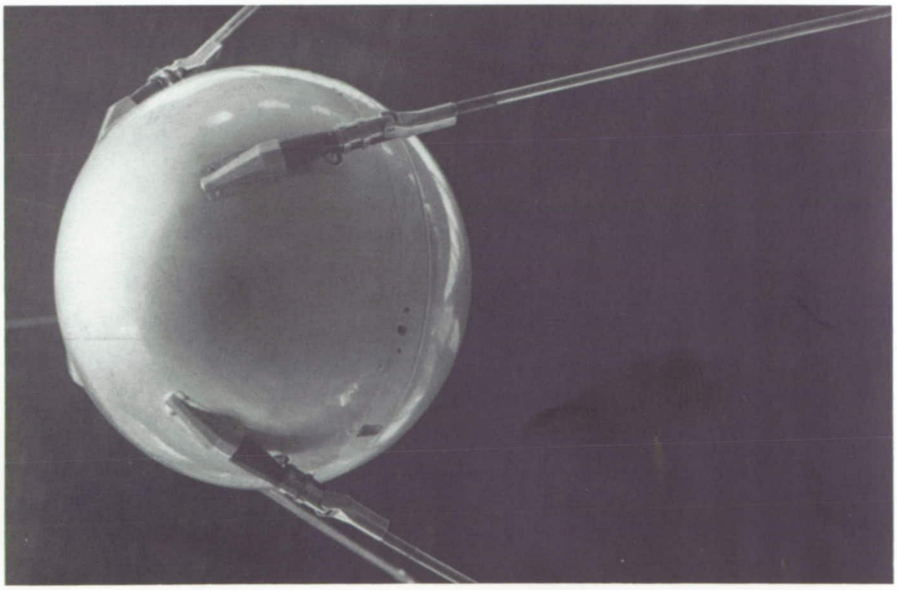
Richard Tangum

Introduction

Human presence in space has expanded dramatically since the first Sputnik of October 1957. Between 1959 and 1976, 40 spacecraft were launched into lunar orbit or to the surface of the Moon.

Spaceflights That Provided Lunar Data

Apollo missions	(1968-1972)	9	manned flights
Luna series	(1959-1976)	13	Russian probes
Surveyor	(1966-1968)	5	unmanned landings
Ranger	(1964-1965)	3	preimpact photography flights
Zond	(1965-1970)	4	unmanned flybys
Lunar Orbiter	(1966-1967)	5	orbital photography flights
Explorer 35	(1967)	1	orbital flight



Sputnik I

The "beep beep" of Sputnik I in October of 1957 changed the world's perception of itself. This full-scale model of the basketball-size satellite was on display at the Soviet Pavilion at the Paris Air Show.

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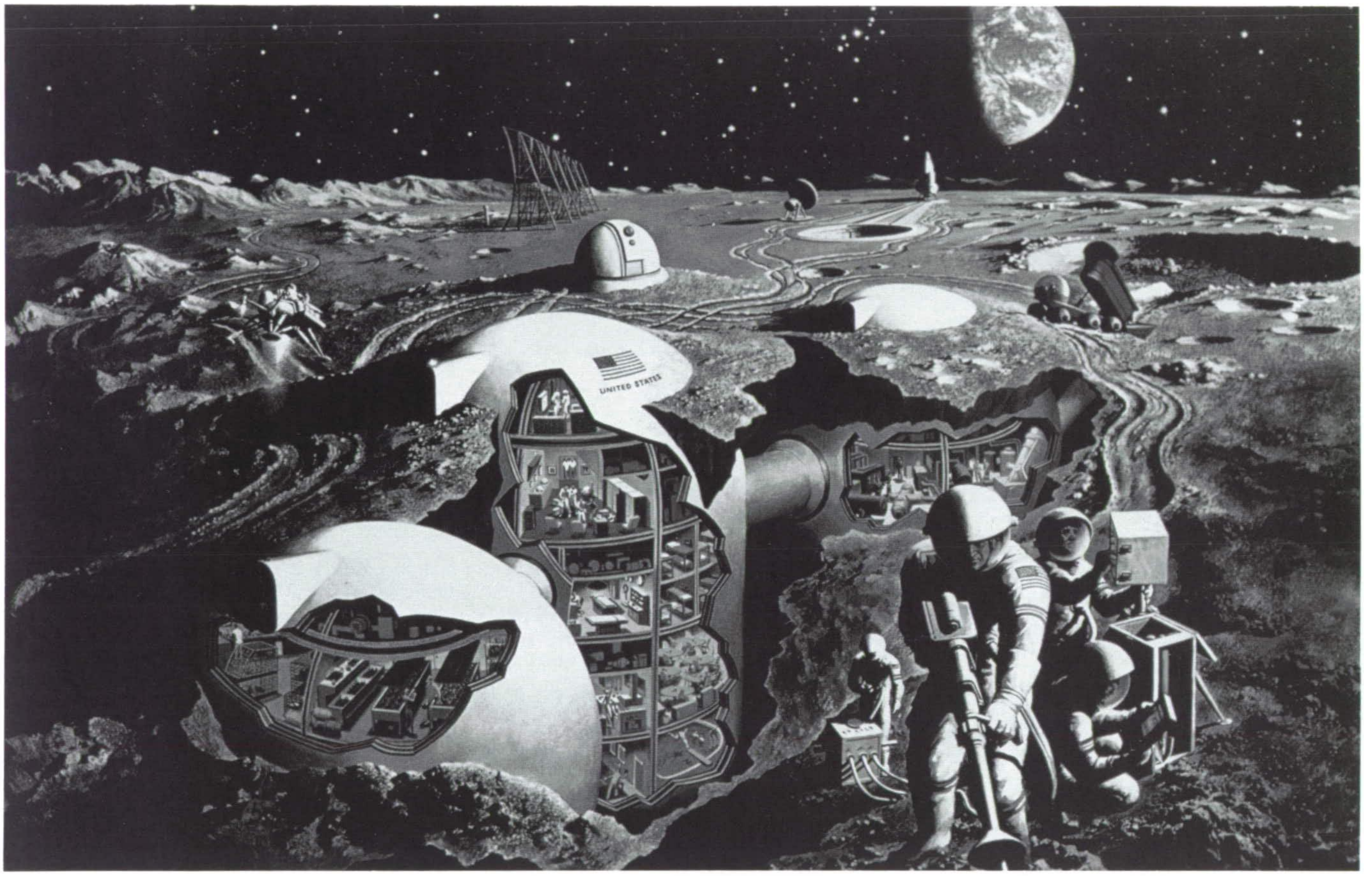
Likewise, the launching of satellites into low Earth orbit (LEO) and geosynchronous Earth orbit (GEO) has continued unabated. This presence in space—to include the lunar surface, asteroids, and Mars—will increase dramatically in scale and scope within the next quarter century. NASA's plans for a space station in LEO are already under way.

The National Commission on Space appointed by President Reagan calls for human outposts on the Moon by 2005 and on Mars by 2115. The Commission believes that an aggressive plan should be adopted

> To lead the exploration and development of the space frontier, advancing science, 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.

The Commission further states that a major thrust should be exploring, prospecting, and settling the solar system. Furthermore, space enterprises should be encouraged to benefit people on Earth. President George Bush, in his speech at the Air and Space Museum on the 20th anniversary of the Apollo 11 landing, both echoed an Apollo 11 astronaut and reinforced the Commission's goals by stating

> Mike Collins said it best: "The Moon is not a destination; it's a direction." And space is the inescapable challenge to all the advanced nations of the Earth. And there's 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. The time has come to look beyond brief encounters. We must commit ourselves anew to a sustained program of manned exploration of the solar system, and, yes, the permanent settlement of space. We must commit ourselves to a future where Americans and citizens of all nations will live and work in space.



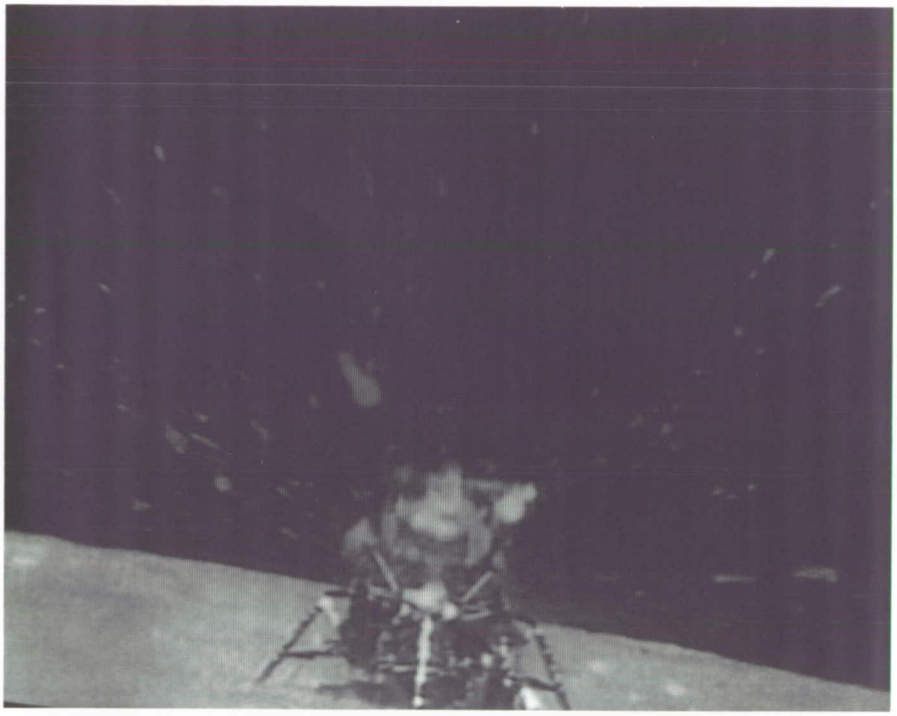
Lunar Colony, as Conceived in February 1969

This painting and its caption, published 5 months before the Eagle *of Apollo 11 touched down on the Moon and brought back the first lunar samples, is remarkable not for its mistakes in detail, which analysis by hundreds of scientists of the nearly 400 kilograms (841 pounds) of lunar rocks collected by the Apollo astronauts has subsequently revealed, but rather for the accuracy of its general idea of facilities and activities that now, "a generation" later, we are planning to build and carry out on the Moon:*

"Frontiersmen of the Space Age, engineers and technicians colonize the moon. Drawing on the most advanced thinking of experts, artist Davis Meltzer portrays a lunar outpost that might be possible in a generation. A survey team drills core samples and maps the surface as an attendant monitors the oxygen supply. Aluminum habitation modules lie almost buried for protection against micrometeorites and temperatures that fluctuate 500°F. between noon and night. In a laboratory module, foreground, biologists observe animals and experiment with raising vegetables in fertilized water. A multi-level main module encloses dressing rooms for entering and leaving, medical dispensary, dormitory, kitchen, and dining and recreation areas. Pressurized tunnel leads to a smelter, where lunar rock quarried on the surface is processed for the water chemically locked within it. The water not only fills the station's swimming pool, but also yields oxygen for breathing and hydrogen for fuel for a flying vehicle, far left. A fencelike radio telescope probes deep space, and an optical scope in a small observatory studies the heavens, undimmed by earth's atmosphere. Beside a hangar pit, a commuter rocket poises for return to the blue planet earth."

Artist: Davis Meltzer

Illustration and caption taken from Kenneth F. Weaver, 1969, "The Moon, Man's First Goal in Space," National Geographic ***135*** *(2—Feb.): 206-230.*



Apollo 16 Lift-Off From the Moon

The confetti-colored sparkles of the lunar module lift-off for each of the last three Apollo missions were seen by millions of people, thanks to a TV camera mounted on the lunar rover. We were glad to see our astronauts lifted safely from that far-off surface to join their fellows in the orbiting command and service modules and come home to Earth. But, as we contemplate going back to the Moon, to establish a permanent base, we must be concerned about the effect that our built environment will have on the natural environment there.

Studies of the potential use of nonterrestrial materials could have far-reaching implications for the environments of low Earth orbit and the lunar surface, in terms of both use and the prevention of possible contamination. A need is clearly emerging for some form of environmental assessment and management to determine what to use space or planetary surfaces for and how to do it; what changes to tolerate and what standards to impose; and how to meet these standards.

The term *environment* in space can be used in three different senses: first, the natural environment of soils, gases, and organisms that may be present; second, the built environment, including manned satellites and the areas humans build to live and work in; third, the social environment—culture, law, and economics. Of immediate concern is the effect of the built environment on the natural environment in space.

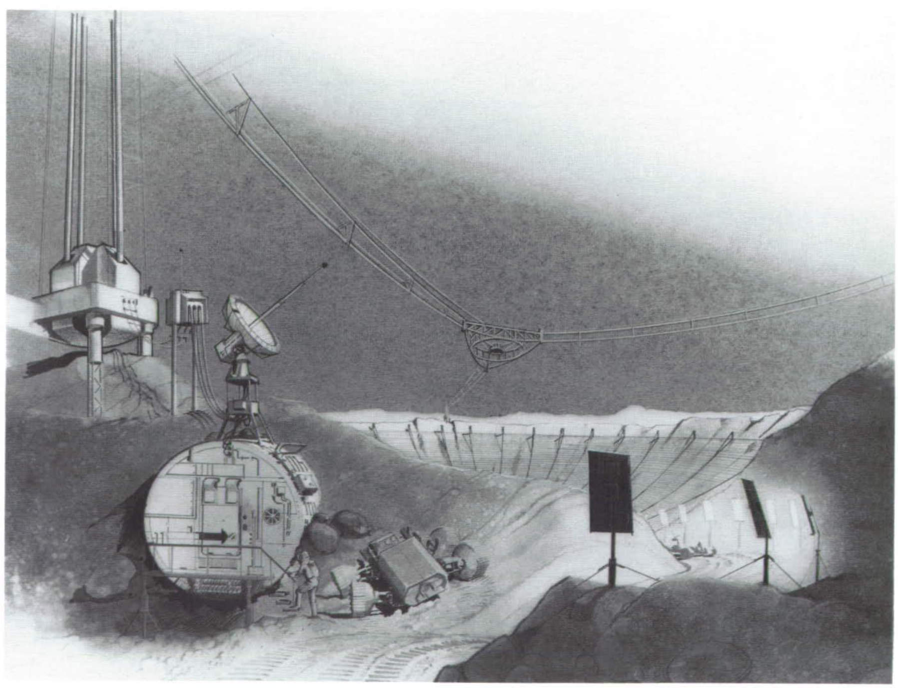
Potential Research

Many of the initial activities potentially associated with the establishment of a lunar base will involve research. A lunar base setting with low gravity and a vacuum environment makes it possible to conduct unique experiments that are not possible on Earth. These factors, plus added seismic stability, make the Moon a perfect observatory platform. The far side of the Moon is especially suited for radio astronomy because its pristine environment, shielded from radio frequencies, allows measurements over a wide range of wavelengths (see fig. 15). Solar wind studies are easier on the Moon because of the lack of an atmosphere and also the lack of a large magnetic field. Furthermore, the Moon acts as an absorbing surface to the charged solar plasma. Geological studies can answer questions about the Moon's history, its evolution, structure, composition, and state. Practical resource development questions will arise about where large quantities of various ores can be found and how to mine them economically.

Figure 15

Radio Telescope on the Far Side of the Moon

In this artist's concept, a radio telescope has been placed in a meteorite crater on the far side of the Moon. The parabolic grid in the crater reflects the signal to the steerable collector suspended by cables. The lunar far side may prove to be an ideal location for radio telescopes because nearly all radio frequency noise generated by human activity on Earth will be blocked out by the Moon itself. In the concept shown here, the radio telescope is human-tended but is operated by remote control most of the time. Information from the telescope is beamed to a lunar communications satellite which relays the data back to Earth. Other radio telescope designs have also been proposed, including large-area phased arrays which do not require parabolic reflectors. While early lunar base installations will likely be on the near side of the Moon, far side sites for radio telescopes will likely follow because of the clear advantage of such a location.



An Illustration of the Problem

Mining of the lunar surface is an area of potential environmental concern. This issue was voiced by the Lunar Base Working Group, meeting at Los Alamos National Laboratory in 1984:

> Most lunar scientific activities require that the unique lunar environment be preserved. Lunar base operations might affect this environment in *adverse* ways, especially if industrial operations expand.

Specific potential environmental impacts were cited: increased atmospheric pressure, which could change atmospheric composition and compromise astronomical observations, and increased very low radio frequency background through satellite communication networks, which could affect the use of the far side of the Moon for radio telescopes.

Unprotected by any atmosphere, the Moon will accumulate scars of impacts by humans at an increasing rate. In contrast, the Earth will exhibit a more youthful appearance, since it is constantly rejuvenated by geological processes such as erosion by wind and water. On the Moon, micrometeoritic action turns over the top 3 mm of the lunar surface every 1 000 000 years (Gault et al. 1975). In this time span, the lunar surface is destroyed, recreated, and shaped.

Extensive mining efforts on the Moon, however, could scar its surface irreversibly. Numerous components of mining on the Moon must be environmentally assessed: the scale of the mining operation, its associated development, and its technological features. Factors affecting the scale of mining include

- Ore quality
- Size of ore body
- Availability of energy
- Cost of operation
- Type of operation

Strip mining would probably be the most efficient method for producing ore (see fig. 16). There could remain the desolation of steep piles of discarded regolith, alternating with the trenches from which the regolith is removed. The Moon, in time, could become a visual and scientific wasteland. Laws requiring backfilling of the trenches and recontouring of the ground surface to some semblance of its original state would be needed.

Development and technological features affecting the environmental impact include

- Size of mining installation (land required)
- Volume of spoil generated
- Nature of energy source used
- Nature of transportation system used
- Nature and volume of pollution released
- Use of explosives
- Drilling processes

Oxidic minerals will probably be the first resource mined on the Moon for life support and rocket propellant. Although projected ore volume for initial production of oxygen would be low (82 cubic meters of unconcentrated fines per day), eventual development of larger settlements would require a vast mining operation to sustain them. Approximately 100 000 tons of regolith (10-percent usable ilmenite content) are needed to produce 1000 tons of oxygen in a carbothermal oxygen production plant (Cutler and Krag 1985). This translates into a mining operation that extracts 50 000 cubic meters of regolith for each 1000 tons of oxygen produced.

Selenopolis, a fully developed lunar settlement envisioned by Krafft Ehricke (1985), could require vast quantities of oxygen per year for its inhabitants' use for life support and rocket propellant. Annually to produce 500 000 tons of oxygen, an area 7.07 kilometers square and 5 meters deep would have to be mined.

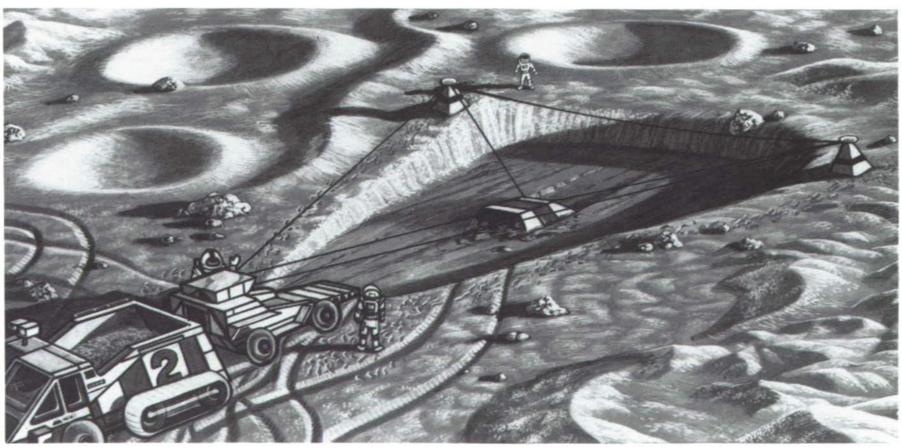


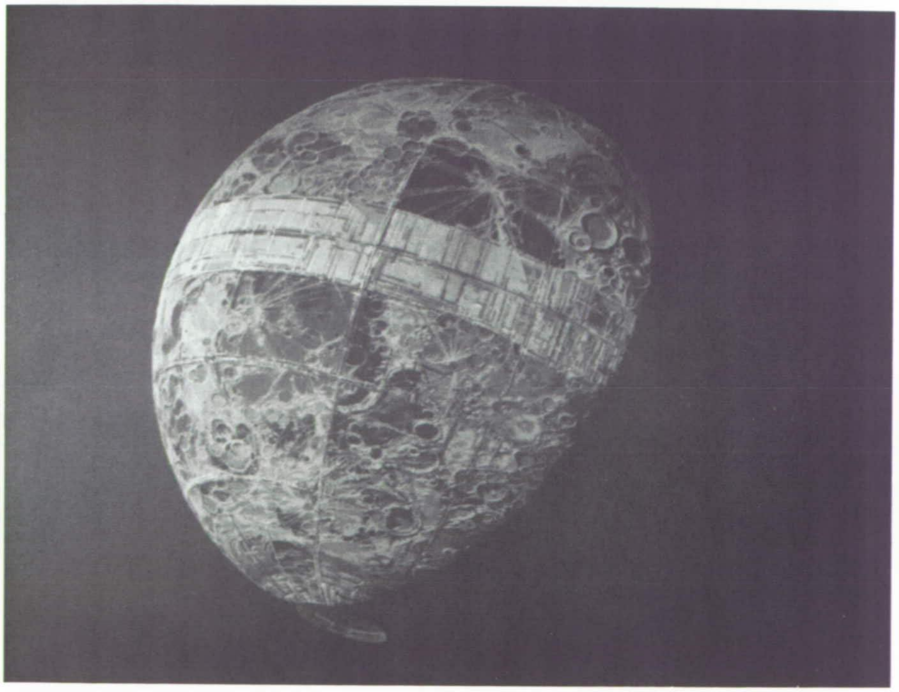
Figure 16

Three-Drum Slusher

This lunar mining system is called a "three-drum slusher." It is similar to a simple two-drum dragline, in which a bucket is pulled by cables to scrape up surface material and dump it into a waiting truck. The third drum allows the bucket to be moved from side to side to enlarge the mining pit. Surface mining of unconsolidated lunar regolith, using versions of draglines or front-end loaders, will probably be done at a lunar base initially, although deeper "bedrock" mining is also a possibility and underground mining may even be attractive if appropriate resources are located.

Although the Moon does not have an atmosphere as such, it does have an exosphere in which individual particles are captured by its gravitational field. Each one of the Apollo missions between 1969 and 1972 added more than 10 tons of exhaust gases to the exosphere. Over the 3-year period, more than 60 tons of gases were released on the lunar surface. And the five Luna missions that returned samples from the Moon between 1970 and 1976 probably added a similar amount. Although subsequent measurements failed to detect their presence, these gases had a sufficiently high molecular weight that their dispersal from the gravitational field of the Moon would occur only through a very slow process. What happened to these gases? A likely answer suggested by Zdenek Kopal (1979) is that the gases were rapidly absorbed by the lunar crust and bound in a solid state. The implications of the release of large quantities of gases of different types is unknown.

We must remember that the Moon, in its pristine condition, serves as an important, well-preserved fossil of the solar system. Much remains to be discovered about the evolution of the Earth and the solar system. Very little geological evidence has



"Moon, 2000"

Would-be developers may find this image of the Moon overly optimistic, at least by the year 2000. But environmentalists like Rick Tangum may view the image, by visual futurist Syd Mead, more pessimistically. Tangum is concerned about the scale of a mining operation necessary to support a large lunar settlement. Unmanaged development of the Moon could destroy its potential to reveal scientific information about the early history of the solar system.

Artist: Syd Mead

been discovered about the first billion years of Earth's 4-1/2 billion year history. Geological discoveries on the Moon will continue to clarify Moon-Earth and solar system history (see box). Unmanaged development of the Moon could destroy this potential.

What We've Learned About the Earth by Studying the Moon

- The Earth formed during the same planetary accretionary period as did the Moon—about 4.5 billion years ago. Much older rocks are found on the dry, airless, rapidly cooled Moon, whose crust has not been eroded and subducted like the Earth's has.
- The Earth, like the Moon, continued to be bombarded by planetesimals from its formation down to about 3.9 billion years ago. This record, too, is preserved on the relatively inactive Moon.
- The most likely story of the origin of the Moon explains why the Moon is less dense than the Earth: A planetesimal the size of Mars collided with the Earth and splashed some of the Earth's mantle, along with the silicate mantle of the impactor, into orbit around the Earth, where the debris accreted to form the Moon. The metallic core of the impactor, on the other hand, accreted to the Earth. This collision tilted the Earth 23° from the plane of the ecliptic and gave it its spin.
- The Earth was once completely molten, allowing its differentiation, the heavier elements sinking toward its still molten core, the lighter elements rising to eventually form its granitic continental crust. Traces of such chemical separations, occurring while the Moon was covered by a "magma ocean," are still preserved in its rocks.
- Even after the period of heaviest bombardment (4.5 to 3.8 billion years ago), impacts by asteroids, meteorites, and comets have continued to be significant, albeit random, events in geological history, though the evidence has been mostly erased on Earth. One such catastrophic impact has been found to be coincident with the extinction of the dinosaurs.
- The eruption of basalts, derived by the partial melting of the mantle, has been common on the solid planets and their satellites and on some asteroids. This igneous process is seen in the dark lava flows that filled the lunar basins we call "maria" (or "seas"), more of them on the near than on the far side of the Moon.

And an unanswered question:

Why does the Moon lack a magnetic field while the Earth has a relatively strong one? Is it because the Moon has only a small, if any metal core? If so, then why is a "fossil" magnetism preserved in lunar rocks?

Compiled from information provided by Michael B. Duke, S. Ross Taylor, John A. Wood, and the Solar System Exploration Division at NASA Headquarters.

Conclusion

The formation of positive attitudes and values concerning the environment of space, as the basis for assuming a wise stewardship role, is becoming increasingly important as many nations begin their journeys into space. A strong emphasis should be placed on fostering an international space environmental ethics.

The object of environmental assessment and management in space should be to define what interplanetary regulatory procedures are needed to avoid unnecessary environmental damage and to monitor the effectiveness of such avoidance. The first requirement for research is to narrow the field of concern to areas where there could be an increased scale of development in space in the immediate future. Research needs to be focused on methodologies for defining the environmental systems involved (e.g., the lunar surface) and then recognizing key variables in the system that are fragile and need to be respected. Criteria for environmental quality should emerge which identify, in the case of the lunar surface, how much mining activity can be safely undertaken and what quantity of exhaust gases can be released over a given period of time. Only then will humans be most able to evaluate the likely consequences of ventures into space and be able to best preserve the newest frontier for posterity.

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Applications of Living Systems Theory to Life in Space*

James Grier Miller

Introduction

Earth, so far as we know, is the only planet in our solar system on which living systems have ever existed. Since Earth's primeval atmosphere lacked free oxygen and therefore had no ozone layer to protect primitive cells and organisms from the Sun's killing radiation, life evolved in the sea for the first two billion years. The biological activity of primitive algae is considered a major factor in creating our oxygen atmosphere, making it possible to colonize land.

Now the human species is contemplating a second great migration, this time into space. Human settlements, first on space stations in orbit and then on bases on the Moon, Mars, and other planetary bodies, are in the planning stage.

Planning for nonterrestrial living requires a reorientation of the long-range strategic purposes and short-range tactical goals and objectives of contemporary space programs. The primary focus must be on the human beings who are to inhabit the projected settlements. This implies a shift in thinking by space scientists and administrators so that a satisfactory quality of human life becomes as important as safety during space travel and residence. Planners are challenged not only to provide transportation, energy, food, and habitats but also to develop social and ecological systems that enhance human life.

Making people the dominant consideration does not diminish the need to attend to technologies for taking spacefarers to their new homes and providing an infrastructure to sustain and support them in what will almost certainly be a harsh and stressful setting (Connors, Harrison, and Akins 1985).

As clear a vision as possible of human organizations and settlements in space and on nonterrestrial bodies in the 21st century should be gained now. A beginning was made by the National Commission on Space (1986) in depicting the human future on the space frontier. Behavioral scientists, particularly those with a general systems orientation, can contribute uniquely to this process. They can do research to improve strategic and programmatic planning focused on human needs and behavior. The results should prove to be the drivers of the mechanical, physical, and biological engineering required to create the space infrastructure.

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When we envision nonterrestrial stays of long duration, we must plan for quite different social phenomena than we have seen in space missions up to now. Astronauts have lived on space stations for periods of a few weeks or months at most. The great majority of missions have been relatively brief. Such missions have required the daring and initiative of carefully selected and highly trained astronauts equipped to accomplish limited goals. If people are to remain permanently in settlements far from Earth, however, they cannot endure the inconvenient, uncomfortable, and difficult working and living conditions that have been the lot of the highly trained and motivated professionals who have gone into space over the past 30 years. Months and years in a space environment are an entirely different matter. Motivation diminishes over time and long-continued discomforts are hard to bear.

Spacelab 1

As technicians examine the Spacelab module, a physician examines a prospective occupant. As we contemplate long journeys to other planets and lengthy stays in space, we must plan not only for the safe transportation and life support of spacefarers but also for their comfort and well-being. The high motivation that has characterized astronauts and cosmonauts in space flights so far cannot be expected to endure avoidable difficulties throughout long missions.

Artist: Charles Schmidt (NASA Art Program Collection)

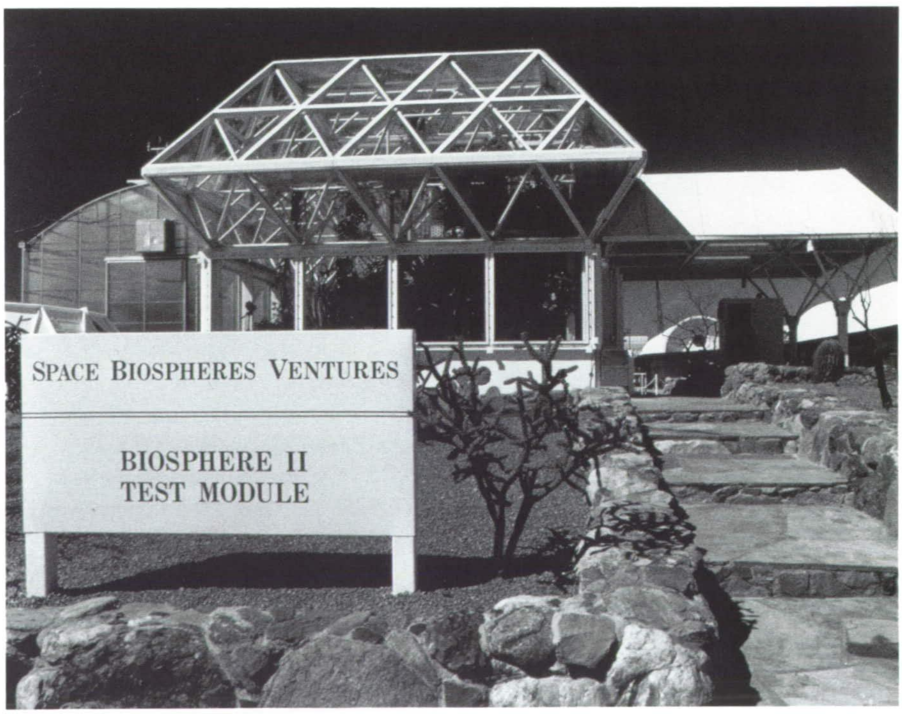
If men, women, and perhaps even children live together in nonterrestrial locations which, even with excellent communications to Earth, are inevitably isolating, their behavior will undoubtedly be different from any that has so far been observed in space. A new space culture may well arise (see Harris's paper on space culture in this volume). This is particularly likely in an international program that includes people from different nations and diverse cultures. It is not too early to begin systematically to try to understand what such settlements will be like in order to plan wisely for them.

No place on Earth closely resembles the conditions in space, on the Moon, or on other planetary bodies. The harsh environmental stresses and the isolation that must be faced by people who winter over in Antarctica, however, are similar in many ways. If the logistical problems of doing research there and the attendant costs can be coped with, perhaps Antarctica is the best place within the Earth's gravity field to analyze the problems of life in space and even to put a space station simulator or to model a lunar outpost. Also it is a good place to develop plans for continuous monitoring of human behavior under rigorous conditions, by procedures such as those based on living systems theory, which is outlined below. If that kind of Antarctic research is infeasible or unduly costly, we can consider doing space station research at other locations, such as the Space Biospheres at Oracle, Arizona, or on space station simulators at Marshall Space Flight Center in Huntsville, Alabama; at McDonnell Douglas Corporation in Huntington Beach, California; or at Ames Research Center at Moffett Field, California.

Researcher notes condition of insect-growing area at Biosphere II

Biosphere II Test Module

On November 2, 1989, botanist Linda Leigh stepped inside an airlock and entered an ecosystem separate from the biosphere of the Earth. For the next 21 days, the air she breathed, the water she drank, and the food she ate were generated by the ecosystem within the 17 000-cubic-foot airtight glass and steel Test Module of Space Biospheres Ventures in Oracle, Arizona. Leigh harvested fruits, vegetables, herbs, and fish grown in the module and prepared them in the module's human habitat section, which includes an efficiency kitchen, a bathroom with a shower, a bed, and a study area with a desk. She communicated with colleagues and observed air and water quality data, by computer monitor. In this, as in the previous two tests, all environmental quality indicators remained well within safety limits and the human inhabitant remained in excellent health and spirits. James Grier Miller suggests the application of measures based on living systems theory to human behavior in such a simulation of life on a space station.



Space Station Trainer

This accurate physical mockup of a space station module is used to train prospective crewmembers in the use of equipment. The Johnson Space Center also has simulators, which, although they do not look from the outside as the actual hardware will look, do give crewmembers the feeling of being in space. It is not possible to make a trainer/simulator that both looks and feels like the real thing. NASA planners also look at analog situations, like the isolated environment at the South Pole, to study how people function under such rigorous conditions.

Synopsis of Living Systems Theory

Living systems theory (LST) provides one possible basis for such research. This is an integrated conceptual approach to the study of biological and social living systems, the technologies associated with them, and the ecological systems of which they are all parts. It offers a method of analyzing systems—living systems process analysis—which has been used in basic and applied research on a variety of different kinds of systems.

Since 1984 my colleagues and I have been examining how LST can contribute to the effectiveness of space planning and management. At the NASA summer study in LaJolla, we focused on strategic planning for a lunar base. Since then a team of behavioral and other scientists has explored ways in which a living systems analysis could be employed by NASA to enhance the livability of the Space Shuttle and eventually of the space station.

The LST approach to research and theoretical writing differs significantly from that commonly followed in empirical science. One reason for this difference is that LST was developed by an interdisciplinary group of scientists rather than representatives of one discipline. Many members of the group were senior professors with national and international recognition in their own specialties. All members had advanced training in at least one discipline. But they agreed on the importance of achieving unity in science, working toward the goal of its ultimate integration by developing general theories. Research concerned with living systems is designed with this goal in mind. It focuses on the following concerns.

1. Compartmentalization of Science

Modern science suffers from structural problems that have their roots in conceptual issues. The organization of universities by departments, and the structure of science generally, emphasizes the separate disciplines. The rewards of academic life are given for becoming expert in a specialty or subspecialty. It is important, however, that, although the major work of science must be done by specialists, they should all realize that they are contributing to a mosaic and that their work fits, like a piece of a jigsaw puzzle, into an overall picture.

In the real world of daily affairs, whether one is dealing with computers and information processing or with housing, finance, legislation, or industrial production, the problems are always interdisciplinary. The problems that face space enterprises are also interdisciplinary. Each major project needs the skills of engineers, lawyers, economists, computer scientists, biologists, and social scientists in different combinations.

2. Inductive General Theory

There are two major stages in the scientific process: first, the inductive stage, and, second, the deductive stage. The inductive stage is logically prior. Scientists begin the first stage by observing some class of phenomena and identifying certain similarities among these phenomena. Then they consider alternative explanations for these similarities and generate hypotheses to determine which explanation is correct.

A goal of science that has been recognized for centuries is the development of both special theories of limited scope and general theories that unify or integrate special theories and cover broader spheres of knowledge. It is usually necessary to start with special theories that deal with a limited set of phenomena. Middle-range theories concerned with a greater number of phenomena come later. Ultimately a body of research based on these leads to general theories that include a major segment of the total subject matter of a field or of several fields.

The desirability and usefulness of general theory is more widely acknowledged in some disciplines, like mathematics and physics, than in others. Unfortunately many students of science and even senior scientists have not been taught about this goal and are unaware of it. Of course scientists, under the principles of the First Amendment and of academic freedom, may generate their hypotheses any way they please. Then they can test or evaluate them by collecting data and either confirm or disprove them. The findings resulting from such a procedure, however, may not have any discoverable relationship to the findings of any other research in the same field.

Voluntary scientific self-discipline in the mature sciences leads researchers to prefer to carry out studies which test hypotheses that distinguish critically between alternative special theories, middle-range theories, and ultimately general theories. The goal of research on LST is to collect data to make deductive tests of hypotheses derived from inductive, integrative theory.

3. Common Dimensions

If scientists or engineers from different fields are to work together, it is desirable that the dimensions and measurements they use be compatible. Experimenters in physical and biological sciences ordinarily make their measurements using dimensions identical to those used by other scientists in those fields, or other units that have known transformations to them.

It should eventually be possible to write transformation equations to reduce dimensions of any of the disciplines of physical, biological, or social science into common dimensions that are compatible with the meter-kilogram-second system of measurement so that specialists in different fields can communicate precisely. Investigators studying LST attempt to use such dimensions whenever it is possible.

If some phenomena of living systems cannot be measured along such dimensions, one or more others may have to be used. If this is done, however, an explicit statement should always be made that those particular dimensions are incommensurable with the established dimensions of natural science. Furthermore, resolute efforts should be made to discover transformation equations that relate them to the established dimensions. Our experience indicates that in many cases this can be done. The use of transformation equations is advocated rather than an attempt to go directly to some system of common dimensions because people in different disciplines often feel that the measures to which they are accustomed are preferable in their own fields. Transformation equations are a reasonable first step to common dimensions.

Comparable dimensions for living and nonliving systems are increasingly useful as matter-energy and information processing technologies become more sophisticated and are more widely employed throughout the world. The design of person/machine interfaces, for example, is more precise and efficient when both sides are measured comparably. Engineers and behavioral scientists are able to cooperate in joint projects much more effectively than they ordinarily have in the past. Such cooperation greatly facilitates space science. Such comparability of dimensions is a main theme of the program projected in this proposal.

4. Coexistence of Structure and Process

It is important not to separate functional (that is, process) science from structural science. Psychology and physiology are process sciences at the level of the organism, and sociology and political science are process sciences at the level of the society. Gross anatomy and neuroanatomy are structural sciences at the level of the organism, and physical geography is a structural science at the level of the society.

A psychologist or neurophysiologist, however, is inevitably limited if she or he cannot identify the anatomical structure that mediates an observed process, and an anatomist can have only a partial understanding of a structure without comprehending its function. Consequently, whenever a process has been identified but the structure that carries it out is not known, it should be an insistent goal of science to identify the structure. The opposite is also true: It should be an insistent goal of science to identify the process or processes that a structure carries out. Often this is disregarded because it is not thought to be urgent. The main reason for this appears to be that, in the academic world, process or functional sciences are administratively separate from, and in poor communication with, their relevant structural sciences (e.g., gross anatomy at the level of the organism or physical geography at the level of the society).

5. Biosocial Evolution

Living systems are open systems that take from the environment substances of lower entropy and higher information content (food, energy, information) than they put back into the environment (waste, heat, noise). This thermodynamically improbable increase of internal information (negative entropy), which does not occur in nonliving systems, makes it possible for them to grow, do work, make products, and carry on other life functions.

On the basis of a mass of supporting scientific evidence, LST asserts that over the last approximately 3.8 billion years a continuous biosocial evolution has occurred, in the overall direction of increased complexity. It has so far resulted in eight *levels* of living systems: cells, organs, organisms, groups, organizations, communities, societies, and supranational systems. This evolution came about by a process of *fray-out* (see fig. 1) in which the larger, higher-level systems evolved with more (and more complex) components in each subsystem than those below them in the hierarchy of living systems. Fray-out can be likened to the unraveling of a ship's cable. The cable is a single unit but it can separate into the several ropes that compose it. These can unravel further into finer strands, strings, and threads.

Systems at each succeeding level are composed principally of systems at the level below. Cells have nonliving molecular components, organs are composed of cells, organisms of organs, groups are composed of organisms, and so on. Systems at higher levels are *suprasystems* of their component, lower-level systems, which are organized into *subsystems*, each of which performs one of the activities essential to all living systems.

Our identification of these subsystems was under way by 1955. By 1965 we had identified 19 of them. A 20th, the timer, was identified only recently (Miller 1990). It is interesting that a group of researchers at Lockheed Corporation in 1985, apparently without any underlying conceptual theory or any knowledge of our previous work, identified a set of elements and subelements of the living and nonliving aspects of a space station with significant similarities to our subsystems. They were not wholly comparable, however. One incompatibility is that the Lockheed researchers listed as elements or subelements not only what we call "subsystems" but also what we call "levels" and "flows."

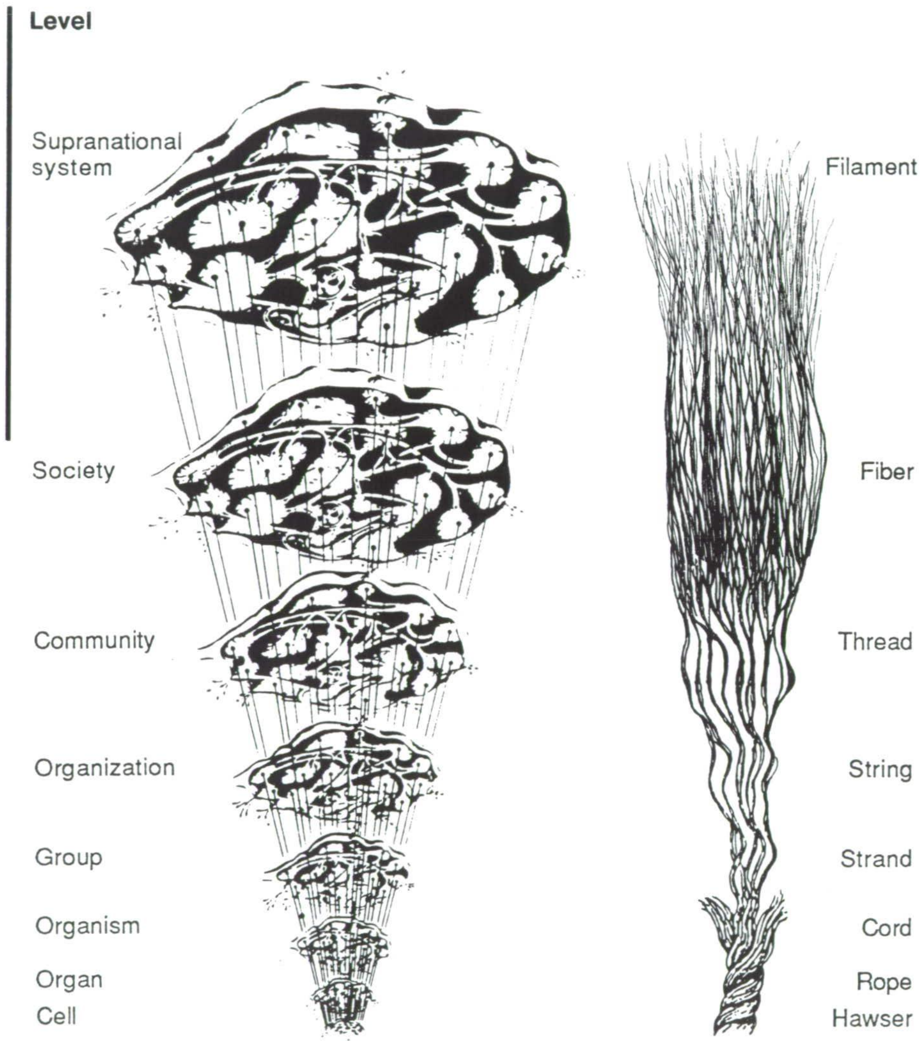


Figure 1

Fray-Out

We can visualize the relationship among the levels of living systems by comparing a cell to a ship's cable. As the more complex levels "fray-out" from their cellular form, they grow and thus produce the larger forms. Each of these levels, small or large, is composed of the same 20 subsystems, however.

6. Emergents

The fact that systems at each level have systems at the level next below as their principal components doesn't mean that it is possible to understand any system as just an accumulation of lower-level systems. A cell cannot be described by summing the chemical properties of the molecules that compose it, nor can an organism be described by even a detailed account of the structure and processes of its organs. LST gives no support to reductionism. At each higher level of living systems there are important similarities to the lower levels, but there are also differences. Higher-level systems have emergent structures and processes that are not present at lower levels. Emergents are novel processes, made possible because higher-level systems have a greater number of components with more complicated relationships among them. It is this increased complexity that makes the whole system greater than the simple sum of its parts, and gives it more capability. Higher-level systems are larger, on average, and more complex than those below them in the hierarchy of living systems. They can adapt to a greater range of environmental variation, withstand more stress, and exploit environments not available to less complex systems.

7. The Subsystems of Living Systems

Because of the evolutionary relationship among them, all living systems have similar requirements for matter and energy, without which they cannot survive. They must secure food, fuel, or raw materials. They must process their inputs in various ways to maintain their structure, reproduce, make products, and carry out other essential activities. The metabolism of matter and energy is the energetics of living systems.

Input, processing, and output of information is also essential in living systems. This is the "metabolism" of information.

LST identifies 20 essential processes which, together with one or more components, constitute the 20 subsystems of living systems (see table 1). With the exception of the 2 subsystems of the learning process, which seem to have evolved with animal organisms, all 20 processes appear to be present at each of the eight levels, although they may not be present in all types of systems at a given level. Bacteria, which are cells, for example, have no motor subsystems but many other types of cells have motor components and can move about in the environment or move parts of the environment with relation to them. Similarly, some groups and organizations process little or no matter-energy. Some systems clearly have components for certain processes but these components have not been identified. This is largely true for organism associating. Even the simplest animals have some form of learning but the components are not certainly known.

TABLE 1. *The Subsystems of Living Systems*

Subsystems which process both matter-energy and information	
1. *Reproducer,* the subsystem which carries out the instructions in the genetic information or charter of a system and mobilizes matter, energy, and information to produce one or more similar systems.	
2. *Boundary,* the subsystem at the perimeter of a system that holds together the components which make up the system, protects them from environmental stresses, and excludes or permits entry to various sorts of matter-energy and information.	
Subsystems which process matter-energy	**Subsystems which process information**
3. *Ingestor,* the subsystem which brings matter-energy across the system boundary from the environment.	11. *Input transducer,* the sensory subsystem which brings markers bearing information into the system, changing them to other matter-energy forms suitable for transmission within it. 12. *Internal transducer,* the sensory subsystem which receives, from subsystems or components within the system, markers bearing information about significant alterations in those subsystems or components, changing them to other matter-energy forms of a sort which can be transmitted within it.
4. *Distributor,* the subsystem which carries inputs from outside the system or outputs from its subsystems around the system to each component.	13. *Channel and net,* the subsystem composed of a single route in physical space or multiple interconnected routes over which markers bearing information are transmitted to all parts of the system. 14. *Timer,* the subsystem which transmits to the decider information about time-related states of the environment or of components of the system. This information signals the decider of the system or deciders of subsystems to start, stop, alter the rate, or advance or delay the phase of one or more of the system's processes, thus coordinating them in time.
5. *Converter,* the subsystem which changes certain inputs to the system into forms more useful for the special processes of that particular system.	15. *Decoder,* the subsystem which alters the code of information input to it through the input transducer or internal transducer into a "private" code that can be used internally by the system.
6. *Producer,* the subsystem which forms stable associations that endure for significant periods among matter-energy inputs to the system or outputs from its converter, the materials synthesized being for growth, damage repair, or replacement of components of the system, or for providing energy for moving or constituting the system's outputs of products or information markers to its suprasystem.	16. *Associator,* the subsystem which carries out the first stage of the learning process, forming enduring associations among items of information in the system.
7. *Matter-energy storage,* the subsystem which places matter or energy at some location in the system, retains it over time, and retrieves it.	17. *Memory,* the subsystem which carries out the second stage of the learning process, storing information in the system for different periods of time, and then retrieving it. 18. *Decider,* the executive subsystem which receives information inputs from all other subsystems and transmits to them outputs for guidance, coordination, and control of the system. 19. *Encoder,* the subsystem which alters the code of information input to it from other information processing subsystems, from a "private" code used internally by the system into a "public" code which can be interpreted by other systems in its environment.
8. *Extruder,* the subsystem which transmits matter-energy out of the system in the forms of products or wastes. 9. *Motor,* the subsystem which moves the system or parts of it in relation to part or all of its environment or moves components of its environment in relation to each other.	20. *Output transducer,* the subsystem which puts out markers bearing information from the system, changing markers within the system into other matter-energy forms which can be transmitted over channels in the system's environment.
10. *Supporter,* the subsystem which maintains the proper spatial relationships among components of the system, so that they can interact without weighting each other down or crowding each other.	

A set of symbols, shown in figure 2, have been designed to represent the levels, subsystems, and major flows in living systems. They are intended for use in simulations and diagrams and are compatible with the standard symbols of electrical engineering and computer science. They can also be used in graphics and flow charts.

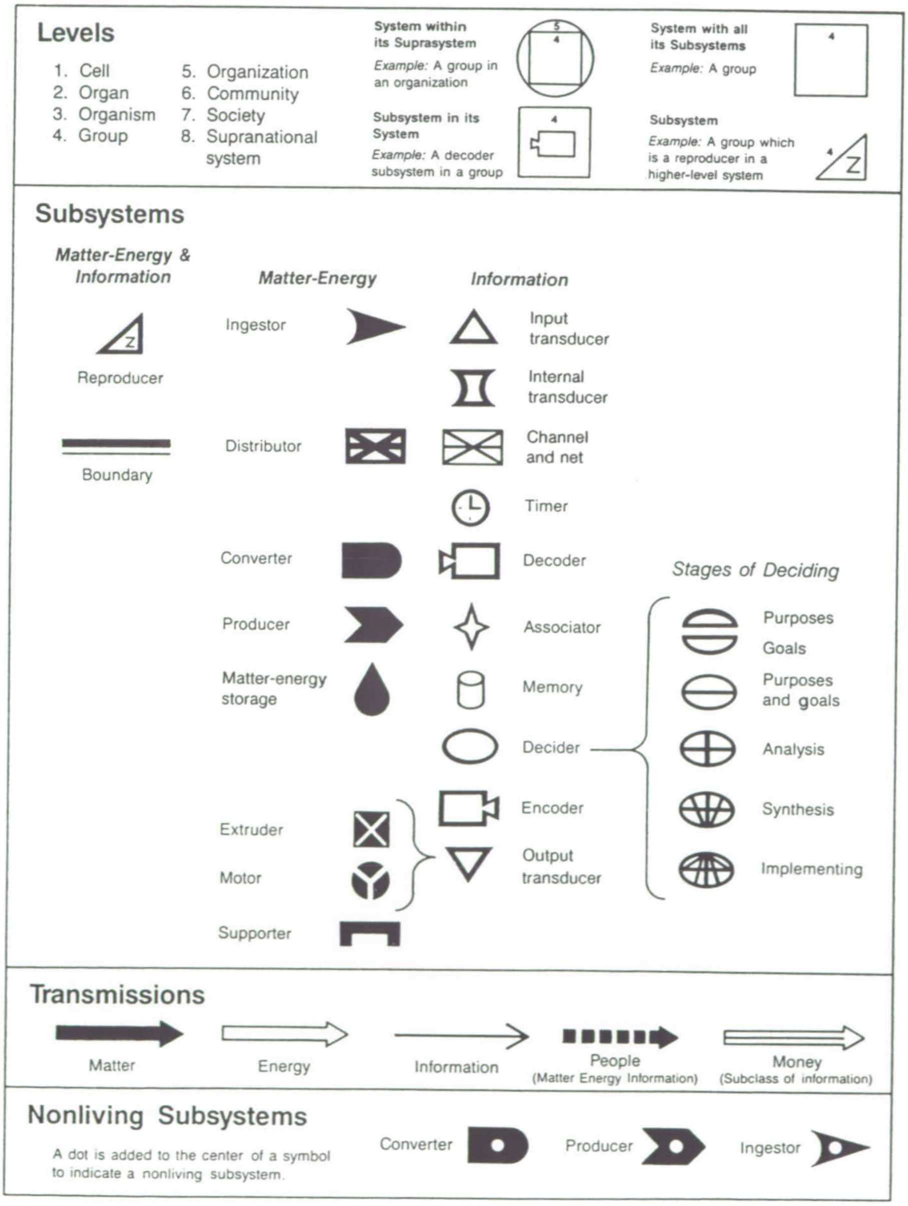


Figure 2

Living Systems Theory Symbols

If a system lacks components for a given subsystem or part of it, it may *disperse* the process to a system at the same or another level. Symbiosis and parasitism are examples. The essential part of the associator subsystem in organizations is downwardly dispersed to human brains, since an organization makes associations only when human subcomponents have done so. An organization may, however, have some components, like a training department, that are involved in the process. It is also possible for

TABLE 2. *Selected Major Components of Each of the 20 Critical Subsystems at Each of the Eight Levels of Living Systems**

Subsystem / Level	Reproducer	Boundary	Ingestor	Distributor	Converter	Producer	Matter-energy storage	Extruder	Motor	Supporter
Cell	DNA and RNA molecules	*Matter-energy and information:* Outer membrane	Transport molecules	Endoplasmic reticulum	Enzyme in mitochondrion	Chloroplast in green plant	Adenosine triphosphate	Contractile vacuoles	Cilia, flagellae, pseudopodia	Cytoskeleton
Organ	Upwardly dispersed to organism	*Matter-energy and information:* Capsule or outer layer	Input artery	Intercellular fluid	Parenchymal cell	Islets of Langerhans of pancreas	Central lumen of glands	Output vein	Smooth muscle, cardiac muscle	Stroma
Organism	Testes, ovaries, uterus, genitalia	*Matter-energy and information:* Skin or other outer covering	Mouth, nose, skin, in some species	Vascular system of higher animals	Upper gastrointestinal tract	Organs that synthesize materials for metabolism and repair	Fatty tissues	Sweat glands of animal skin	Skeletal muscle of higher animals	Skeleton
Group	NASA officer who selects astronauts for crew	*Matter-energy:* Inspectors of covering of spacecraft *Information:* Crew radio operator	Astronauts who bring damaged satellite into spacecraft	Crewmember who distributes food	Dispersed to maker of packaged rations	Crewmembers who repair damaged equipment	Crewmember who stows scientific instruments	Crew that ejects satellite into orbit	Downwardly dispersed to individual members	Crewmembers who maintain spacecraft
Organization	Dispersed upward to society that creates space agency	*Matter-energy:* NASA inspectors of contracted equipment *Information:* NASA guards who arrest intruders	Receiving department of NASA center	Conveyer belt in factory that makes parts for space habitat	Workers who stamp out parts for space vehicle	Doctors who examine astronauts	Workers who store supplies on space vehicle	Janitors in NASA buildings	Driver of gantry crane	Janitors in launch site buildings
Community	Space agency that establishes space station	*Matter-energy:* Dispersed to builders of habitat *Information:* Operators of downlink to Earth	Receivers of materials from Shuttle	Food servers in dining facility	Organization that mines Moon	Medical organization in space community	Workers who put supplies into storage areas	Mine organization that sends minerals to Earth	Drivers of Moon surface vehicles	Maintenance crew of habitat buildings
Society	Constitutional convention that writes national constitution	*Matter-energy:* Customs service *Information:* Security agency	Immigration service	Operators of national railroads	Nuclear industry	All farmers and factory workers of a country	Soldiers in Army barracks	Export organizations of a country	Aerospace industry that builds spacecraft	Officials who operate national public buidings and lands
Supranational system	United Nations when it creates new supranational agency	*Matter-energy:* Troops at Berlin Wall *Information:* NATO security personnel	Legislative body that admits nations	Personnel who operate supranational power grids	EURATOM, CERN, IAEA	World Health Organization	International storage dams and reservoirs	Downwardly dispersed to societies	Operators of United Nations motor pool	People who maintain international headquarters buildings

systems that lack a given process to use an alternative process to accomplish a similar effect. Individual bacteria cannot adapt to the environment by learning, since they lack associator and memory subsystems, but bacterial colonies do adapt by altering the expression of genes. Components of the 20 subsystems at each level of living systems are listed in table 2.

Similar variables can be measured in each subsystem at all levels. These are such things as quantity, quality, rate, and lag in flows of matter, energy, or information.

TABLE 2 *(concluded).*

Subsystem Level	Input transducer	Internal transducer	Channel and net	Timer	Decoder	Associator	Memory	Decider	Encoder	Output transducer
Cell	Receptor sites on membrane for activation of cyclic AMP	Repressor molecules	Pathways of mRNA, second messengers	Fluctuating ATP and NADP	Molecular binding sites	Unknown	Unknown	Regulator genes	Structure that synthesizes hormones	Presynaptic membrane of neuron
Organ	Receptor cell of sense organ	Specialized cell of sinoatrial node of heart	Nerve net of organ	Heart pacemaker	Second echelon cell of sense organ	None found; upwardly dispersed to organism	None found; upwardly dispersed to organism	Sympathetic fiber of sinoatrial node of heart	Presynaptic region of output neuron	Presynaptic region of output neuron
Organism	Sense organs	Proprioceptors	Hormonal pathways, central and peripheral nerve nets	Supraoptic nuclei of thalamus	Sensory nuclei	Unknown neural components	Unknown neural components	Components at several echelons of nervous system	Temporoparietal area of dominant hemisphere of human cortex	Larynx; other components that output signals
Group	Crewmember who receives messages from ground control	Crewmember who reports crew's reactions to life in capsule	Astronauts who communicate person to person	Dispersed to all members who hear time signals	Member who explains coded message	Dispersed to all members who learn new techniques	Dispersed to all crewmembers	Captain of crew in capsule	Members who write reports of space experience	Members who report to Mission Control
Organization	NASA secretaries who take incoming calls	Representative of employees who reports to executive	Users of NASA internal phone network	Office responsible for scheduling flights	Experts who explain specs to contractors	People who train new employees	Filing department	NASA executives, department heads, middle managers	Public relations staff	Administrator who makes policy television speech
Community	Operators of downlink to Earth	Communicator over downlink to Earth	Psychologists who report on morale of spacefarers	Caretakers of clocks in community	Users of communication system in space station	Engineers who interpret building blueprints	Scientists who do research in space	Central computer of space community	Commanding officer and staff	Officer who writes report to Earth station
Society	Foreign news services	Public opinion polling organizations; voters	Telephone and communications organizations	Legislators who decide on time and zone changes	Cryptographers	All teaching institutions of a country	Keepers of national archives	Voters and officials of national government	Drafters of treaties	National representatives to international meetings
Supranational system	UN Assembly hearing speaker from nonmember territory	Speaker from member country to supranational meeting	INTELSAT	Personnel of Greenwich observatory	Translators for supranational meetings	FAO units that teach farming methods in Third World nations	Librarians of UN libraries	National representatives to international space conferences	UN Office of Public Information	Official who announces decisions of supranational body

*Note: The components listed in table 2 are examples selected from many possible structures of each subsystem and at each level. At the organism level, animals are chosen in preference to plants, although many components of plants are comparable. In general, examples are from human rather than animal groups, although similar structures exist in many other species. Only human beings form systems above the group. Table 2 places special emphasis on living systems involved in space exploration and habitation. At each level the examples of subsystem components are from different types of systems. This choice makes it clear that the analysis applies to various sorts of systems. At the level of the group and above, components involved in communications rather than monetary flows are used as examples in information processing subsystems. This is done because monetary flows, while obviously important, are found only in human systems and are currently not very significant in space habitations.

8. Adjustment Processes

Living systems of all kinds exist in an uncertain environment to which they must adapt. Excesses or deficits of necessary matter-energy or information inputs can stress them and threaten their continued well-being or even their existence. In the midst of flux, they must maintain steady states of their innumerable variables.

Each system has a hierarchy of values that determines its preference for one internal steady state rather than another; that is, it has *purposes*. These are comparison values that it matches to information inputs or internal transductions to determine how far any variable has been forced from its usual steady state. A system may also have external *goals*, such as finding and killing prey or reaching a target in space.

All living systems have *adjustment processes*, sometimes called "coping mechanisms," that they can use to return variables to their usual steady states. These are alterations in the rates or other aspects of the flows of matter, energy, and information. Subsystems also match the state of each variable they control with a comparison signal and use adjustment processes to correct deviations from it. In general, more adjustment processes are available to higher level systems than to those at lower levels.

Countless small adjustments take place continually as a living system goes about its essential activities. Minor deviations can often be corrected by a single component of one subsystem. More serious threats are countered by a greater number of subsystems or all of them. Severe deviations from steady state constitute pathology that a system may not be able to correct.

The six classes of adjustment processes vary the input, internal, and output processing of matter and energy (matter-energy) and information.

All adjustment processes are used at some cost to the system. Ordinarily a system that survives chooses the least costly of its alternatives.

9. Cross-Level Research

Because of the similarities that exist across all levels of life, empirical cross-level comparisons are possible and are the sort of basic research that is most characteristic of living systems science. Since the evolution of the levels has occurred in physical space-time, their comparable subsystems and variables can ultimately be measured in meter-kilogram-second or compatible units.

Research to test cross-level hypotheses began in the 1950s and continues to the present (Miller 1986a). Such research can provide accurate and dependable fundamental knowledge about the nature of life that can be the basis for a wide range of applications.

LST research strategy: The following strategy is used to analyze systems at any level. It has been applied to systems as different as psychiatric patients and organizations.

1. Identify and make a two- or three-dimensional map of the structures that carry out the 20 critical subsystem processes in the system being studied (see table 2).

2. Identify a set of variables in each subsystem that describe its basic processes. At levels of group and below, these represent aspects of the flows of matter, energy, and information. At levels of organization and above it has proved useful to measure five instead of three flows: MATFLOW, materials; ENFLOW, energy; COMFLOW, person-to-person, person-to-machine, and machine-to-machine communications information; PERSFLOW, individual and group personnel (who are composed of matter and energy and also store and process information); and MONFLOW, money, money equivalents, account entries, prices, and costs—a special class of information.

3. Determine the normal values of relevant variables of every subsystem and of the system as a whole and measure them over time, using appropriate indicators.

The normal values of innumerable variables have been established for human organisms. A physician can make use of reliable tests and measurements and accepted therapeutic procedures to discover and correct pathology in a patient. Similar information is not available to the specialist who seeks to improve the cost-effectiveness of an organization. Studies that make it possible to generalize among organizations are few, with the result that the usual values of most variables are unknown at organization and higher levels. This lack makes it difficult to determine to what extent an organization's processes deviate from "normal" for systems of its type. Pathology in an organization may become apparent only when deviation is so great that acceptance of the organization's products or services declines or bankruptcy threatens.

4. Take action to correct dysfunctional aspects of the system and make it healthier or more cost-effective, by, for example, removing a psychiatric patient from an unfavorable environment, altering the structure or process of a work group, or introducing nonliving artifacts (like computers or faster transport equipment) into an organization.

Our proposed study would apply the above strategy to evaluating the cost-effectiveness of the operations of a crew of a space station, tracking the five categories of flows through its 20 subsystems, identifying its strengths and dysfunctions, and recommending ways to improve its operations. Later a similar approach could be applied to a mission to Mars, a lunar settlement, and perhaps other human communities in space. It could also be used at Antarctic bases.

Validation of LST: LST arises from the integration of a large number of observations and experiments on systems of a variety of types that represent all eight levels. As with other scientific theories, however, its assertions cannot be accepted without validation.

How have some of the well-known theories been validated? Consider, for example, Mendeleyev's periodic table of the elements, first published in the mid-19th century. In its original form, it was based on a hypothesis that the elements could be arranged according to their atomic weights and that their physical properties were related to their place in the table. Revisions by Mendeleyev and others over succeeding years led to discovery of errors in the assigned atomic weights of 17 elements and included new elements as they were discovered, but the properties of some required that several pairs of elements be reversed. In the early 1920s, after the discovery of atomic numbers, a hypothesis by van den Brock that the table would be correct if atomic number rather than atomic weight were used as its basis was confirmed by H. G. J. Moseley's measurement of spectral lines. The present form of the table places all known elements in correct order and has made it possible to predict the characteristics of elements to be discovered in nuclear reactions.

Confirmation of Mendeleyev's theory required testing of a succession of hypotheses based on it. No theory can be considered valid until such observation and research have shown that its predictions about the real systems with which it is concerned are accurate.

If LST is to have validity and usefulness, confirmation of hypotheses related to it is essential. The first test of an LST hypothesis was a cross-level study of information input overload at five levels of living systems, carried out in the 1950s (Miller 1978, pp. 121-202). It confirmed the hypothesis that comparable information input-output curves and adjustment processes to an increase in rate of information input would occur in systems at the level of cell, organ, organism, group, and organization. Numerous other quantitative experiments have been done on systems at various levels to test and confirm cross-level hypotheses based on living systems theory (e.g., Rapoport and Horvath 1961, Lewis 1981). Such tests support the validity of living systems theory.

Applications of Living Systems Theory

Living systems theory has been applied to physical and mental diagnostic examinations of individual patients and groups (Kluger 1969, Bolman 1970, Kolouch 1970) and to psychotherapy of individual patients and groups (Miller and Miller 1983). An early application of LST at organism, group, and organization levels was a study by Hearn in the social service field (1958).

An application of living systems concepts to families described the structure, processes, and pathologies of each subsystem as well as feedbacks and other adjustment processes (Miller and Miller 1980). A subsystem review of a real family* was carried out in a videotaped interview that followed a schedule designed to discover what members were included in each of several subsystems, how the family decided who would carry out each process, how much time was spent in each, and what problems the family perceived in each process.

Research at the level of organizations includes a study of some large industrial corporations (Duncan 1972); general analyses of organizations (Lichtman and Hunt 1971, Reese 1972, Noell 1974, Alderfer 1976, Berrien 1976, Rogers and Rogers 1976, and Merker 1982, 1985); an explanation of certain pathologies in organizations (Cummings and DeCotiis 1973); and studies of accounting (Swanson and Miller 1989), management accounting (Weekes 1983), and marketing (Reidenbach and Oliva 1981). Other studies deal with assessment of the effectiveness of a hospital (Merker 1987) and of a metropolitan transportation utility (Bryant 1987).

*Personal communication (videotape and script) from R. A. Bell, 1986.

The largest application of LST has been a study of the performance of 41 U.S. Army battalions (Ruscoe et al. 1985). It revealed important relationships between characteristics of matter-energy and information processing and battalion effectiveness.

A research study is being conducted in cooperation with IBM, applying living systems process analysis to the flows of materials, energy, communications, money, and personnel in a corporation, in order to determine its cost-effectiveness and productivity. Discussions of possible use of living systems process analysis to evaluate cost-effectiveness in Government agencies are under way with the General Accounting Office of the United States.

Several researchers (Bolman 1967; Baker and O'Brien 1971; Newbrough 1972; Pierce 1972; Burgess, Nelson, and Wallhaus 1974) have used LST as a framework for modeling, analysis, and evaluation of community mental health activities and health delivery systems. LST has also provided a theoretical basis for assessing program effectiveness in community life (Weiss and Rein 1970).

After a pretest of comparable methods of evaluation, a study of public schools in the San Francisco area was carried out (Banathy and Mills 1985). A more extensive study of schools in that area is now in process under a grant from the National Science Foundation.

The International Joint Commission of Canada and the United States has been using living systems theory as a conceptual framework for exploring the creation of a supranational electronic network to monitor the region surrounding the border separating those two countries (Miller 1986b).

Other applied research studies are in planning stages, and proposals are being prepared for some of them. These include an investigation of how to combine bibliographical information on living systems at the cell, organ, and organism levels by the use of computer software employing living systems concepts; an analysis of insect behavior in an ant nest; and a study of organizational behavior and organizational pathology in hospitals.

The conceptual framework of LST and its implications for the generalization of knowledge from one discipline to another have been discussed by many authors (see Miller 1978 and *Social Science Citation Index* 1979 ff.).

It is too early to make a definitive evaluation of the validity of living systems theory. Not enough studies have been carried out and not enough data have been collected. It is possible to say, however, that the theory has proved useful in conceptualizing and working with real systems at seven of the eight levels. Studies at the eighth level, the organ, have not so far been carried out but these will be undertaken in the future. In addition, the general consensus of published articles about the theory has been supportive.

A Proposed LST Space Research Project

It appears probable that the space station that is now in the planning stage at NASA will become a reality in the next few years. It would be a prototype for future nonterrestrial communities—on the Moon and on Mars.

The crew of such a station would include not only astronauts but also technicians and other personnel. They would spend a much longer time in the space environment than crews of space vehicles on previous missions had spent.

Our research method would use LST process analysis to study the space station crew, identify its strengths and dysfunctions, evaluate the performance of personnel, and recommend ways to improve the cost-effectiveness of its operations.

Until the space station is in operation, we would study human activities on modules of a simulated space station. The method used in this phase could later be applied to the space station and eventually to settlements on the Moon or on Mars.

The basic strategy of LST process analysis of organizations is to track the five flows—matter, energy, personnel, communication, and monetary information—through the 20 subsystems and observe and measure variables related to each. Since money flows would probably be unimportant in the early stages of a space station, only the first four are relevant to the first phase of this research. A larger and more permanent space settlement might well have a money economy.

We would measure such variables as rate of flow of essential materials; lags, error rates, and distortion in information transmissions; timeliness of completing assigned tasks; and time and resource costs of various activities.

Data Collection

We plan to collect both subjective and objective data.

Subjective data would consist of responses by personnel to questions about their activities related to the variables under study. Questions would be presented and answered on computer terminals. Responses would be collected in a centralized knowledge base for analysis by a computerized expert system.

In addition to these subjective reports, our research design includes the use of objective indicators or sensors to monitor flows in all subsystems and components and measure them on a real-time basis. A time series of data about them would be transmitted or telemetered to the knowledge base in the computer.

In addition to standard measures of units of energy, quantities of material, bits of information, and the usual personnel records, we plan to make use of a novel technical innovation to monitor the movements of personnel and materials. It consists of badges similar to the ordinary ID badges worn by personnel in many organizations. Each badge contains an infrared transponder in the form of a microchip that, on receipt of an infrared signal from another transponder on the wall, transmits a stream of 14 characters that identifies the person or object to which the badge is attached. With this equipment it is possible to locate in 0.7 sec any one of up to 65 000 persons or materials such as equipment, furniture, weapons, ammunition, or food. If desired, the phone nearest to a person's present location can be rung in another 0.3 sec.

In this way many aspects of processes such as the response time of personnel to questions or commands, the average time spent in various activities, the patterns of interactions among people, and the movement of equipment to different parts of the space station can be measured without unduly disrupting the day-to-day activities of the system.

All the data on the five major flows from questionnaires and objective indicators would be stored in a single computer. Such data could help NASA officials evaluate the effects on space station operations of changes in policy or procedure. In addition, measurements of variables over time make it possible to determine norms for them and to identify deviations that may show either special strengths or dysfunctions. With such information, a computerized expert system can analyze the relationships among the different variables of the five major flows and suggest ways to improve the space station's effectiveness.

Figure 3 is a diagram of the space station showing how the five flows, MATFLOW, ENFLOW, COMFLOW, PERSFLOW, and MONFLOW, might go through its subsystems. The subsystems are identified by the symbols shown in figure 2. Even when only the primary flows of each sort in the space station are superimposed in a diagram like figure 3, they form a very complex pattern.

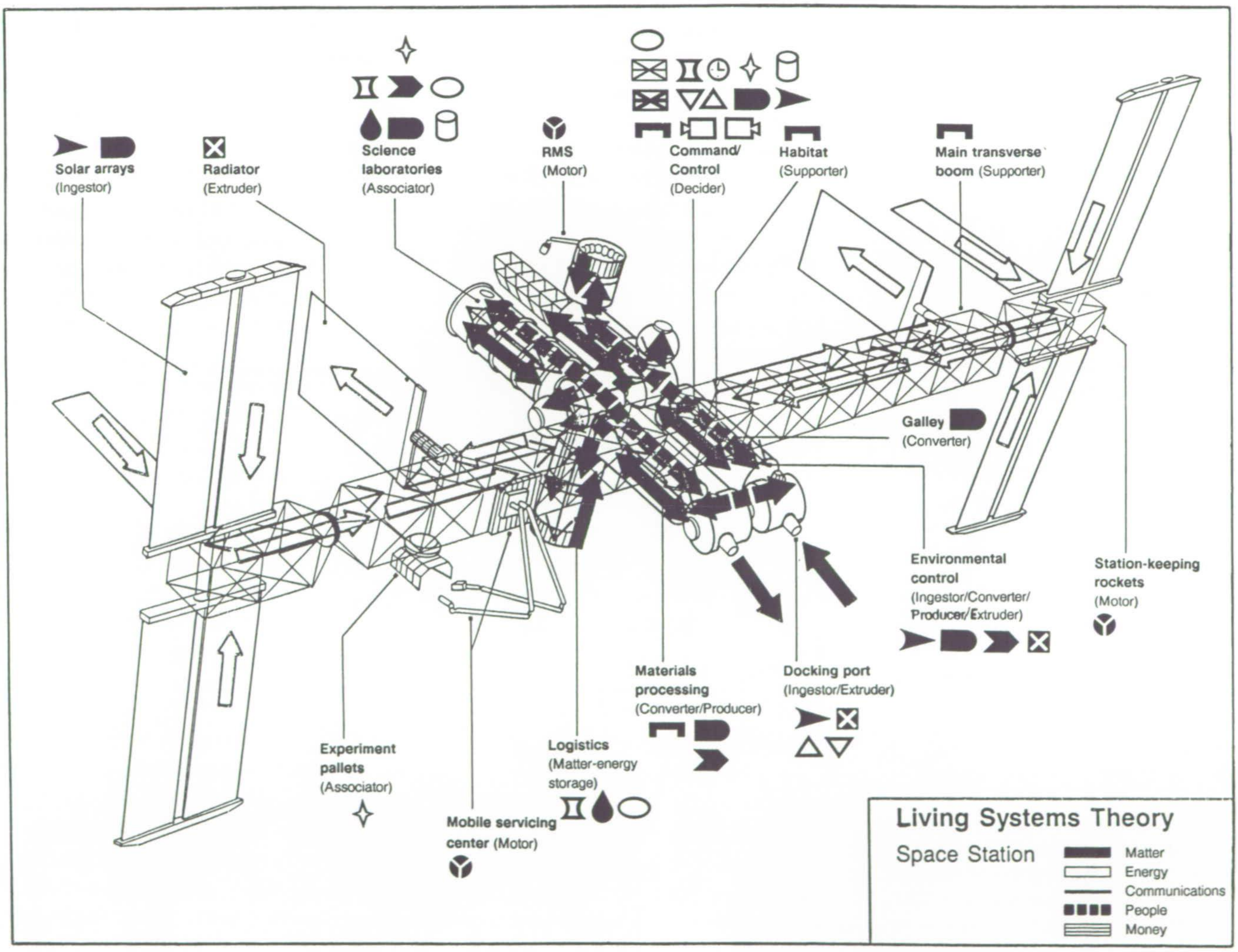


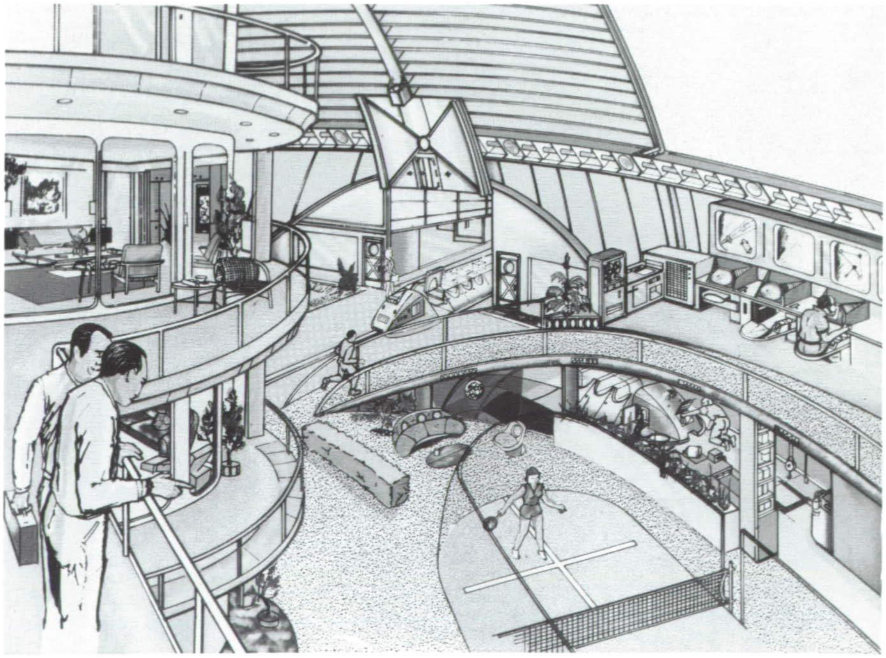
Figure 3

The Five Flows in the Subsystems of the Space Station

In a real space situation, use of monitoring would be of value in many ways. It could identify and report technological or human problems as they occurred. Badges would make it easy for each spacefarer to be found at all times. The officer of the watch would be able to see instantly on a screen the location of all crewmembers with active badges. In addition, the computer could be programmed to present possible solutions to problems and even to initiate necessary steps to assure continuation of mission safety and effectiveness in the event of in-flight emergencies or breakdowns.

Analyzing such flows in subsystems of the space station would provide experience with a novel system for monitoring both living and nonliving components of future space habitations. This experience could well lead to use of similar methods on manned missions to the Moon or to Mars.

For instance, some time in the next century such procedures could be applied to a lunar outpost, a community that would include men, women, and children. A wide range of professional interests, expertise, abilities, and perhaps cultures might be represented in



Monitoring the Movement of People and Equipment at a Space Base

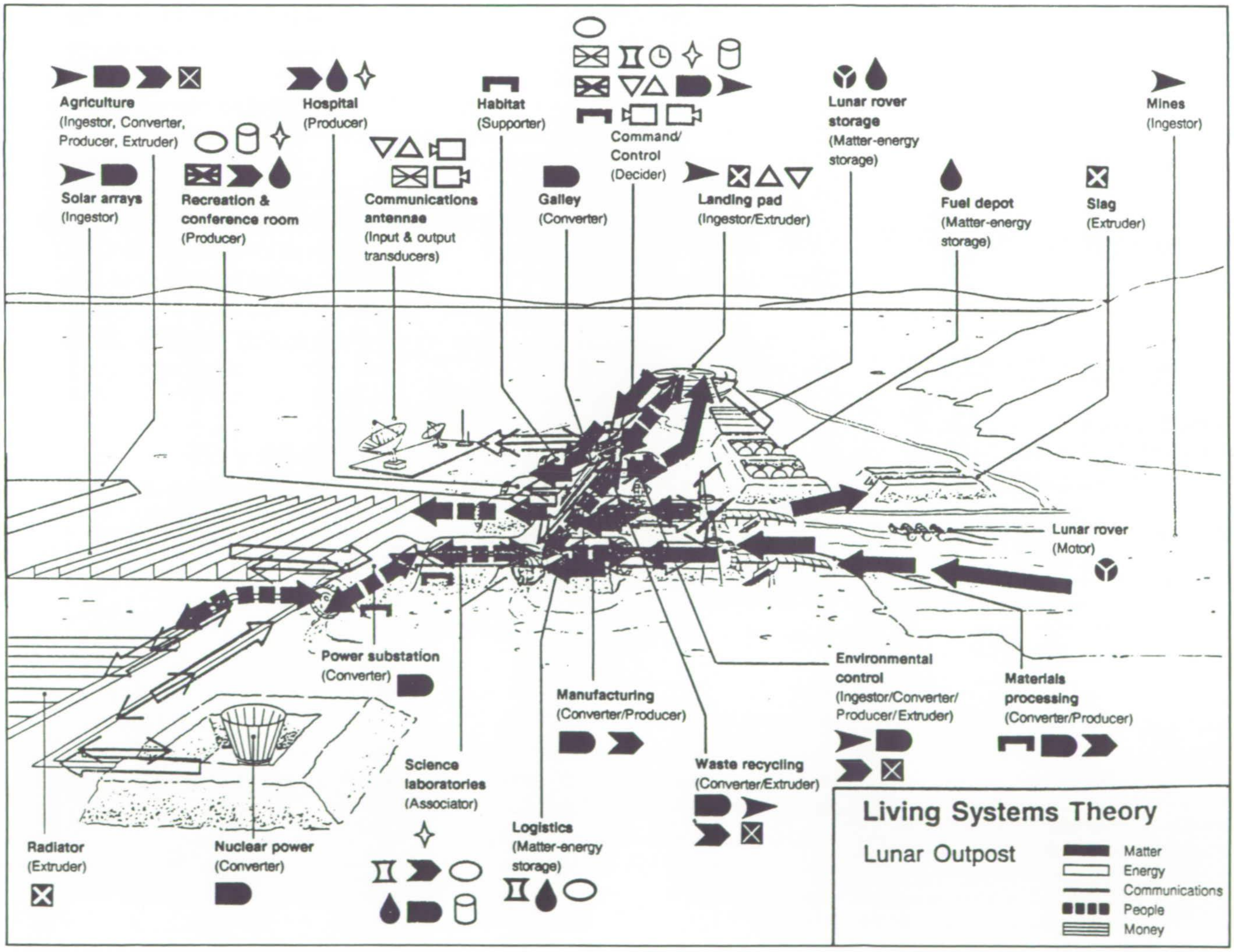
Identification badges containing tiny transponders could track the movements of the woman playing tennis in this space base or the man running on the track. Similarly, property tags with such microchips could report the up-to-the-second location of the monorail train and guard the artwork and plants against theft. Communication of the microchip transponders with transponders mounted on walls would continually report the movements of both personnel and materials to a computerized expert system. If the man servicing the monorail train on the lower level were to get hurt, such automatic monitoring could summon aid in 1 second. And analysis by living systems theory methods could determine whether the interaction between the two men on the walkway is an insignificant waste of time, an important social encounter, or a vital part of an informal communications network.

the lunar community. Residents would live for long times under at least 6 feet of earth or other shielding, which would provide protection from solar radiation, solar flares, and other lunar hazards.

Figure 4 shows such a lunar outpost with designated areas for a command center, habitation, solar power collection, a small nuclear power plant, lunar mines, a solar furnace to use the direct rays of

Figure 4

The Five Flows in the Subsystems of a Lunar Outpost



the Sun for smelting ore and heating the station, a factory, a slag heap, a farm, recycling oxygen and hydrogen, waste disposal, and lunar rovers to transport materials and people on the surface of the Moon from one part of the community to others, as well as for travel outside the immediate area. The five flows through the 20 subsystems of this community are diagramed as were those of the space station shown in figure 3.

Conclusion

The conceptual system and methology of living systems theory appear to be of value to research on life in isolated environments. A space station, which must provide suitable conditions for human life in a stressful environment that meets none of the basic needs of life, is an extreme example of such isolation.

A space station would include living systems at levels of individual human beings, groups of people engaged in a variety of activities, and the entire crew as an organization. It could also carry living systems of other species, such as other animals and plants. Using the subsystem analysis of living systems theory, planners of a station, either in space or on a celestial body, would make sure that all the requirements for survival at all these levels had been considered. Attention would be given not only to the necessary matter and energy (including artifacts such as machinery and implements) but also the equally essential information flows that integrate and control living systems. Many variables for each subsystem could be monitored and kept in steady states.

Use of living systems process analysis of the five flows of matter-energy and information would assure that all members of the crew received what they needed, that distribution and communication were timely and efficient, and that the command centers within the station and on Earth were fully informed of the location and activities of personnel, particularly during an emergency.

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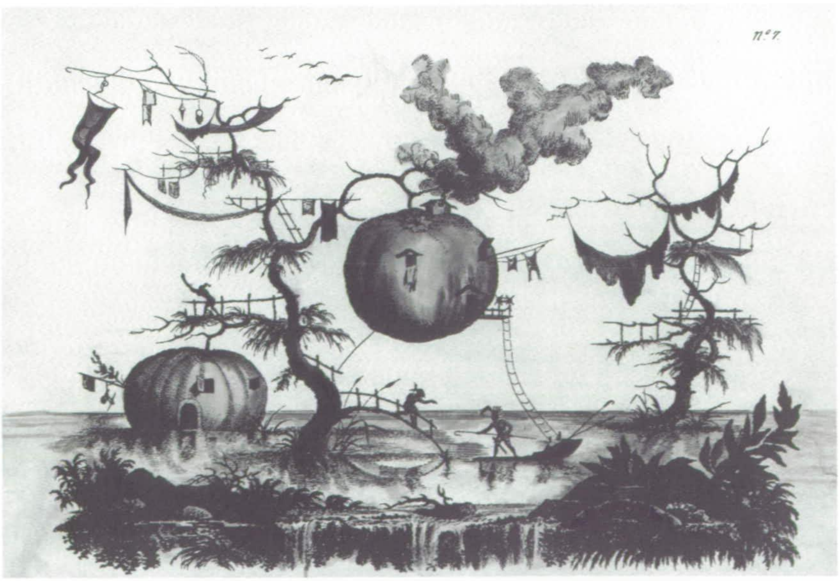
Life Support and Self-Sufficiency in Space Communities

Karl R. Johansson

The development of a controlled ecological life support system (CELSS) is necessary to enable the extended presence of humans in space, as on the Moon or on another planetary body. Over a long period, the provision of oxygen, water, and food, and protection from such inimical agents as radiation and temperature extremes, while maintaining the psychological health of the subjects, becomes prohibitively expensive if all supplies must be brought from Earth. Thus, some kind of a regenerative life support system within an enclosure or habitat must be established, thereby cutting the umbilicus to Mother Earth, but not irreversibly. This protective enclosure will enable the survival and growth of an assemblage of terrestrial species of microorganisms, plants, and animals. I envision that the nonterrestrial ecosystem will evolve through the sequential introduction of terrestrial and local materials, together with the appropriate living forms.

Lunar Characteristics

The principal constraints on life on the Moon are (1) a hard vacuum; (2) apparent lack of water; (3) lack of free oxygen, (4) paucity of hydrogen, carbon, and nitrogen; (5) intense radiation, periodically augmented by solar flares; (6) wide temperature fluctuations at extremes harmful to life; (7) a 2-week diurnal rhythm; and (8) gravity only 1/6 that on Earth.



17th-Century Vision of Life on the Moon

In this fanciful picture of life on the Moon by a 17th-century artist, none of the constraints we now know of are in evidence. The atmospheric pressure appears to be just right for bird flight. Water is plentiful. The cloud of smoke testifies to the presence of carbon and oxygen. The hydrogen and nitrogen needed to sustain plant and animal life are apparent in the lush growth, including the pumpkin-like abodes for the human inhabitants and the cloth flags (or is it the wash?) hung out on poles and limbs. These inhabitants seem to need no heavy clothing to protect them against hazardous radiation or temperature extremes. Though there may be a long night ahead, this scene seems set in the middle of a long, lazy day. And gravity, though not strong enough to pull a "pumpkin" off a tree, is sufficient to hold the people to the floor of their barge, bridge, or balcony.

Artist: Filippo Morghen

Source of illustration: Library of Congress, Rare Book Division

Taken from Davis Thomas, ed., 1970, Moon: Man's Greatest Adventure *(New York: Harry N. Abrams, Inc.), p. 69.*

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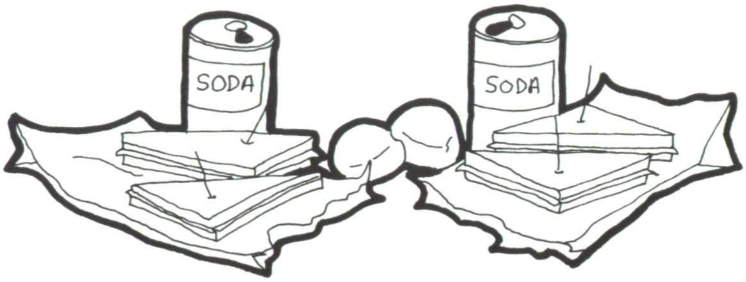
Chemistry and Nutrition

Lunar regolith as a cover for the habitat would shield the ecosystem from radiation and from both high and low temperatures. The enclosure would need to be airtight to contain a life-sustaining atmosphere of O_2, CO_2, N_2, and H_2O vapor. Presumably oxygen would be provided through the reductive processing of oxide ores. From a hydrogen reduction process, the product water could be used. With the establishment in the enclosure of photosynthesis by eucaryotes (algae and higher plants), reliance on ore processing for life-support oxygen would diminish, although that capacity should remain in place as a backup. Additional water, as needed, would continue to be provided externally, although the amounts would be small because, in a properly functioning CELSS, all water is recycled and appropriately treated to render it potable (free of infectious or toxic agents).

The lunar regolith could also provide elements implanted there by the solar wind. These elements include hydrogen and carbon, which could be used to manufacture water and carbon dioxide, and gaseous nitrogen (see box). However, the levels of these elements are low (100-150 ppm), and thus their recovery may prove to be uneconomical. In that case, they would have to be transported from Earth until the CELSS matured. Even then, more oxygen, carbon, and nitrogen would need to be introduced into the system periodically as the human and domestic animal population of the habitat increased or as the recycling process became imbalanced. As with oxygen, tanks of compressed carbon dioxide and nitrogen should be on hand to cope with such perturbations. Both air and water would need to be biologically and chemically monitored.

The Moon contains all of the "trace elements" known to be necessary for life; e.g., magnesium, manganese, cobalt, tin, iron, selenium, zinc, vanadium, and tungsten. The trace elements are absolutely critical to all species of life, largely as cofactors or catalysts in the enzymatic machinery. While their diminution would slow down the ecosystem, a sudden flush of certain trace elements known to be toxic above certain concentrations would be detrimental to some of the component species. I hope that the microbial flora which becomes established in the ecosystem will be able to minimize the extent of fluctuation of the trace elements through its collective adsorptive and metabolic functions. This issue will need to be considered in the selection of the microbial species for introduction into the CELSS.



Lunar Lunch

The Moon has been underrated as a source of hydrogen, carbon, nitrogen, and other elements essential to support life. Each cubic meter of typical lunar soil contains the chemical equivalent of lunch for two—two large cheese sandwiches, two 12-oz. sodas (sweetened with sugar), and two plums, with substantial carbon and nitrogen left over.

Although no free water has been found on the Moon, its elemental constituents are abundant there. One constituent, oxygen, is the most abundant element on the Moon; some 45 percent of the mass of lunar surface rocks and soils is oxygen. The other constituent, hydrogen, is so scarce in the lunar interior that we cannot claim to have measured any in erupted lavas. Nevertheless, thanks to implantation of ions from the solar wind into the grains of soil on the lunar surface, there is enough hydrogen in a cubic meter of typical lunar regolith to yield more than 1-1/2 pints of water.

Similarly, carbon and nitrogen have also been implanted from the solar wind. The amount of nitrogen in a cubic meter of lunar regolith is similar to the amount of hydrogen—about 100 grams, or 3 percent of the nitrogen in a human body. The amount of carbon is twice that; the carbon beneath each square meter of the lunar surface is some 35 percent of the amount found tied up in living organisms per square meter of the Earth's surface.

All of these elements except oxygen can be extracted from the lunar soil simply by heating it to a high temperature (>1200°C for carbon and nitrogen), and some oxygen comes off with the hydrogen. Thus, the problem of accessibility of hydrogen, carbon, and nitrogen reduces to one of the economics of heating substantial quantities of lunar soil, capturing the evolved gases, and separating the different gaseous components from each other. Although water could no doubt be extracted from martian soil at a much lower temperature and organic compounds could probably be extracted at a somewhat lower temperature from an asteroid that proved to be of carbonaceous chondrite composition, the Moon is much closer than Mars and its composition is much better known than that of any asteroid.

Collection of even a small fraction of the Moon's budget of hydrogen, carbon nitrogen, phosphorus, sulfur, and other elements essential to life into a suitable environment on the Moon would support a substantial biosphere.

Taken from Larry A. Haskin, 1990, Water and Cheese From the Lunar Desert: Abundances and Accessibility of H, C, and N on the Moon, in The 2nd Conference on Lunar Bases and Space Activities of the 21st Century *(in press), ed. W. W. Mendell (Houston: Lunar & Planetary Inst.).*

Radiation

The surface of the Moon receives from the Sun lethal levels of high-energy electromagnetic radiation, frequently exacerbated by solar flares of varying duration. Without appropriate protection, no living creature, from microbe to man, could survive the onslaught of this radiation. It has been estimated that approximately 2 meters of regolith will absorb this radiation, thereby protecting the human and nonhuman occupants.

Just how much radiation will penetrate various protective shields still needs to be determined. Undoubtedly, radiation-induced mutations will occur; some will be lethal; others may be incapacitating; and still others may result in mutants better able to cope with the lunar environment than the parental organisms. Of particular concern is the likelihood of mutation among many of the microorganisms constituting the ecosystem, thereby endangering the cycling of the critical elements in the lunar CELSS.

Temperature

With proper attire, humans can withstand, at least for short periods, temperature extremes as high as 50°C and as low as -90°C. The extremes on the Moon exceed these limits by a wide margin. Moreover, other species within the CELSS module would be either killed or suppressed by such extreme temperatures. Obviously, the temperature of a CELSS must be maintained within a moderate range, such as 15 to 45°C, to enable the growth and reproduction of living forms. While many types of psychrophilic and thermophilic microorganisms abound on Earth, their introduction into the CELSS would be useless because neither the food crops to be grown therein nor the human beings harvesting those crops can withstand the temperatures they require.

Regulation of the temperature within a CELSS must take into account radiant energy from the Sun and the release of energy from biological and mechanical activity within the confines of the habitat. The former can be minimized by the protective blanket of regolith required for radiation protection. Efflux of heat from the interior of the habitat may require provision of active or radiative cooling.

Energy for Life

All living forms require an adequate food supply and a source of energy. Among animals and humans, energy is derived from the metabolism of various organic constituents of the diet; e.g., carbohydrates, lipids, proteins, and other nutrients. While many microorganisms gain energy (and carbon) from the oxidation of organic compounds, including methane, many also derive energy from the oxidation of reduced inorganic compounds; e.g., sulfides, ammonia, nitrites, Fe^{++}, and hydrogen. Photosynthetic forms of life (some bacteria, the algae, and the higher plants) can convert photons of energy into chemical bond energy with the photolysis of water and the evolution of molecular oxygen. The energy thus realized is used in the synthesis of carbohydrate (from carbon dioxide and water), which the plants can further metabolize to meet their needs or which can be eaten by animals and humans to supply their energy needs.

It is clear that the requirements for food and energy are interrelated and that the various metabolic processes in the complex food chain affect the availability of nutrients to all the species. Light is a particularly important source of energy because the process of photosynthesis must go on in order for molecular oxygen, required by all but the anaerobic forms of life (principally bacteria), to be regenerated from water. It will probably be necessary, however, to regulate the light synchrony if crop production is to be successful, because 2 weeks of dark and 2 of light will not enable normal plant growth, though special strains might be developed. At the poles, perpetual sunlight could probably be obtained on selected mountains, thus enabling an Earth-like photocycle to be created by periodic blocking of the sunlight (see fig. 5). Elsewhere, artificial light will have to be used to break up the 2-week night.

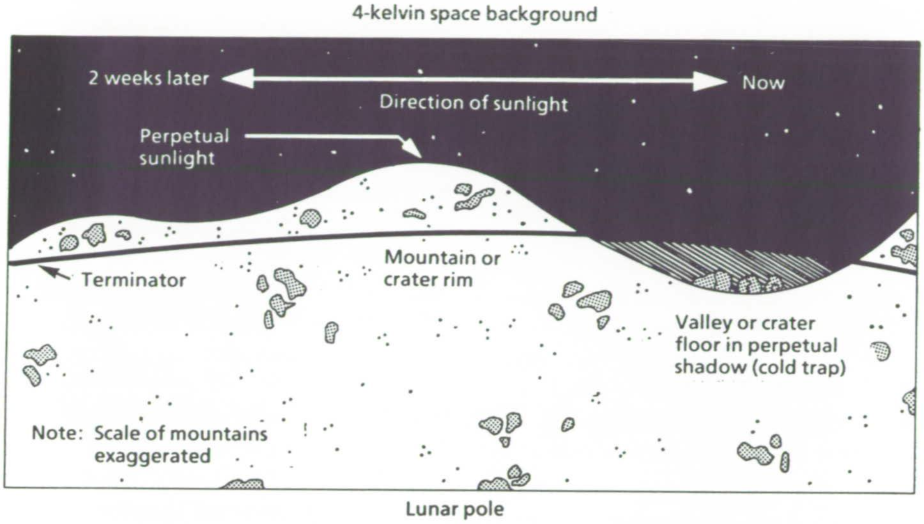
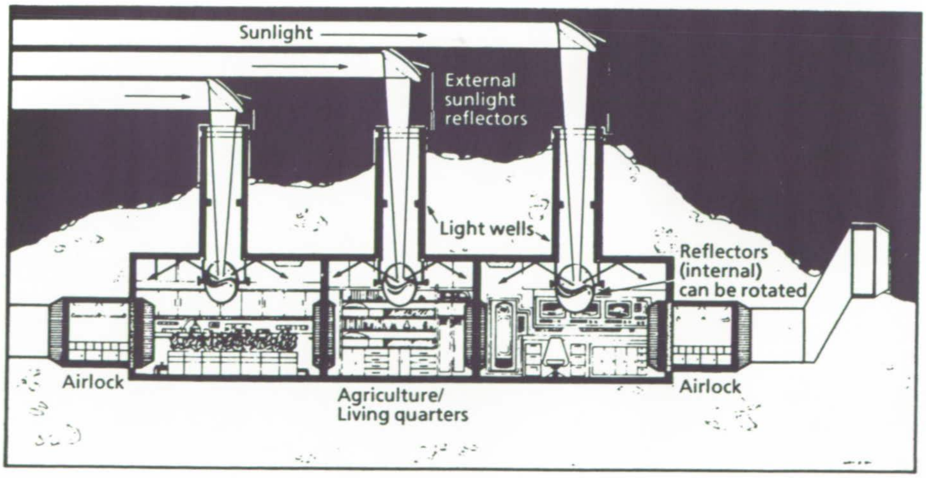


Figure 5

a. Lunar Polar Illumination

The Moon's diurnal cycle of 14 Earth days of sunlight followed by 14 Earth days of darkness could be a problem for siting a lunar base dependent on solar energy or cryogenic storage. A site that might obviate this problem would be at one of the lunar poles. At a pole, high points, such as mountain tops or crater rims, are almost always in the sunlight and low areas, such as valleys or crater floors, are almost always in the shade. The Sun as seen by an observer at the pole would not set but simply move slowly around the horizon. Thus, a lunar base at a polar location could obtain solar energy continuously by using mirrors or collectors that slowly rotated to follow the Sun. And cryogens, such as liquid oxygen, could be stored in shaded areas with their constant cold temperatures.



b. Polar Lunar Base Module

Light could be provided to a lunar base module located at the north (or south) pole by means of rotating mirrors mounted on top of light wells. As the mirrors tracked the Sun, they would reflect sunlight down the light wells into the living quarters, workshops, and agricultural areas. Mirrors at the bottom of the light wells could be used to redirect the sunlight or turn it off.

Gravity

Investigations of the effects of reduced gravity (0.167 g on the Moon) on human physiology and performance and on fundamental life processes in general are being supported and conducted by NASA. Astronauts from the Apollo and other short-term space missions have experienced the well-known, and reversible, vestibular effect (motion sickness) and cephalic shift of body fluids (facial puffiness, head congestion, orthostatic intolerance, and diminution of leg girth). (See figure 6.) Longer-term weightlessness, as experienced by the Skylab astronauts and the Salyut cosmonauts, is more complex, resulting in cardiovascular impairment, atrophy of muscle, reduction in bone mass through osteoporosis (loss of calcium), hematologic changes (leading to immunosuppression and diminished red blood cell mass), neuroendocrine perturbations, and other pathophysiological changes. Some of these effects may be minimized by routine exercise, and apparently all are reversible, in time, upon return to 1 g. The response of plants, microorganisms, and "lower forms" of animal life to micro- or zero gravity has been investigated on Skylab, on Space Shuttle missions (see fig. 7), and in simulations on Earth, during parabolic flight of aircraft or in a "clinostat." Unless humans and other life forms can adapt to zero g, or to low g as on the Moon or Mars, it may be necessary to provide rotating habitats to achieve the desired gravitational force, as many authorities have long proposed.

Figure 6

Lower Body Negative Pressure Device

Principal Investigator John Charles tries out the lower body negative pressure device on a parabolic flight of the KC-135, while its designer, Barry Levitan, looks on from behind him, with project engineer Pat Hite on the side. This accordion-like collapsible version of a device used on Skylab creates a vacuum that pulls the subject's blood into the lower half of the body, just as if the person had suddenly stood up. Its purpose is to prepare the astronaut for return from weightlessness to Earth's gravity and keep that person from blacking out. Mission Specialists Bonnie Dunbar and David Low tested the lower body negative pressure device, which was fabricated at the Johnson Space Center, on Space Shuttle flight 32, January 9-20, 1990.

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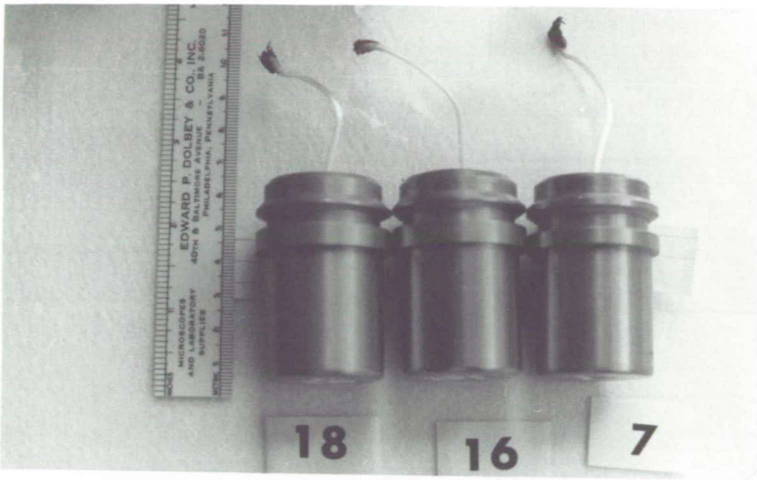

Figure 7

Seedlings Grown on Spacelab 1

These seedlings of Helianthus annuus *(dwarf sunflowers) were planted by Payload Specialist Ulf Merbold for Heflex, the Helianthus Flight Experiment, conducted in Spacelab 1. Upon being removed from the gravity-inducing centrifuge on which they had sprouted and being placed in microgravity, these seedlings continued to circumnutate, thus proving that Charles Darwin was right in thinking that this spiral growth process is intrinsic to plants, not a response to gravity. The curvature of the seedlings is their response to gravity upon return to Earth at the end of Space Shuttle flight 9, November 28-December 8, 1983.*

Heflex is part of an ongoing study of plant response, which will continue in IML-1, the International Microgravity Lab, to be flown on the Space Shuttle in 1991. In two experiments in the part of IML-1 called the Gravitational Plant Physiology Facility, scientists will try to determine the threshold at which oat seedlings can detect gravity and the threshold at which wheat seedlings respond to blue light in the absence of gravity.

Photo: David K. Chapman, Co-Investigator

Selection of Species for an Ecosystem

The greatest challenge in the ultimate establishment of a true space habitat is the creation of a functioning, reliable ecosystem, free, insofar as possible, of pathogens, noxious plants, venomous insects, etc. Moreover, the integrity of a working ecosystem would need to be preserved and its functions monitored regularly.

While it is easy to propose the inclusion of particular species of bacteria, fungi, algae, and higher plants, each of which performs a particular biochemical function in the recycling of nutrients, no rationale exists by which one can predict which particular combination of species would be compatible under the conditions extant in the lunar environment. Considerably more research must be done on closed and semi-closed ecosystems before the organisms for a lunar CELSS are selected (see fig. 8). Conceivably, any number of combinations of species may be found to work well. One point must be stressed: More than one species of organism must be selected to carry out each particular function. Thus, several species of photosynthetic, nitrogen-fixing, nitrifying, or sulfur-oxidizing bacteria must be included. Likewise, a number of species of algae and higher plants, each with the common characteristic of being photosynthetic, must be introduced into the community. Such redundancy, which exists to a vast degree on Earth, provides a kind of buffer in case some of the species lose their niches in the ecosystem and die.

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Figure 8

Zeoponics Plant Growth Chamber at NASA's Johnson Space Center

In this step toward a controlled ecological life support system (CELSS) for a lunar base, plants are being grown in varying mixtures of zeolite and quartz sand. (Zeolite is an aluminosilicate mineral that is able to freely exchange constituent ions with other ions in solution without any apparent change in its mineral structure.) Wheat plants (soft red winter wheat, Coker 68-15) have shown the most favorable response in zeoponics systems consisting of 25 to 75 percent zeolite compared to other zeolite treatments and a commercial potting soil. This research is being conducted by Doug Ming and Don Henninger.

Some Special Aspects of Life in the CELSS

In the first place, the smaller the CELSS, the more magnified becomes any biological, chemical, or physical aberration. No doubt human occupants of the first CELSS module would need more help from the outside at the beginning than they would later on, when numerous connected modules were in place.

The dieback of some support species may well occur from time to time. This would need to be monitored, so that appropriate measures could be taken to reintroduce another strain of the lost species or to introduce an entirely different species with comparable biochemical properties. Reasons for loss of a species in an artificial ecosystem include (1) mutation, (2) temporary tie-up of a critical nutrient, (3) a flush of toxic ions or compounds, (4) malfunction of the temperature control system, (5) a sudden shift in the synchrony of food cycling, and (6) infection or toxemia. The last reason may be particularly troublesome since it will not be possible to assure the exclusion of infectious or toxic microorganisms from the habitat. Many members of the body's normal microflora are opportunistic and can, under certain circumstances, cause disease. Also, plant diseases may emerge if care is not exercised in the initial entry of seeds or of other materials which may contain plant pathogens.

Any animals (e.g., chickens, goats, dwarf pigs) ultimately selected for the space habitat should have been raised in a pathogen-free environment on Earth and tested thoroughly for the presence of any microbial pathogens before their introduction. Gnotobiotic ("germ-free," devoid of a microflora) animals, however, should not be considered because upon exposure to the nonsterile environment of the CELSS they would undoubtedly die of overwhelming infections; such animals have very immature immune systems.

Humans chosen to occupy the CELSS should be protected against certain infectious diseases (e.g., poliomyelitis, measles, whooping cough, and typhoid fever) and bacterial toxemias (e.g., tetanus, diphtheria, and perhaps botulism) by the administration of appropriate vaccines and toxoids. While it would not be possible to assure the total lack of serious pathogenic microorganisms in the human inhabitants, all candidates should be checked microbiologically to assess their carrier state.

The very potent tool of genetic engineering no doubt will be useful in establishing strains of microorganisms or plants with special properties, making it possible to introduce (1) better food crops, (2) organisms with special metabolic functions, and (3) disease-resistant plants.

While this treatise is directed at a lunar ecological system, it is worth noting that a laboratory in low Earth orbit or one in a modified external tank placed in orbit by a Space Shuttle offers certain advantages over the lunar environment as a place to establish and study space ecosystems for application elsewhere, as on Mars, where water and carbon dioxide exist in relative abundance.

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Human Safety in the Lunar Environment

Robert H. Lewis

Any attempt to establish a continuously staffed base or permanent settlement on the Moon must safely meet the challenges posed by the Moon's surface environment. This environment is drastically different from the Earth's, and radiation and meteoroids are significant hazards to human safety. These dangers may be mitigated through the use of underground habitats, the piling up of lunar material as shielding, and the use of teleoperated devices for surface operations.

The Lunar Environment

The Moon is less dense than the Earth and considerably smaller. Its density indicates that the Moon's bulk composition is also somewhat different from Earth's, although it is still a terrestrial (rocky) body. The Moon's surface gravity is only one-sixth the Earth's. And, with its consequently lower escape velocity, the Moon cannot maintain a significant atmosphere. Thus, the surface is directly exposed to the vacuum of space. Lacking an atmospheric buffer, the Moon has a surface temperature that varies over several hundred degrees Celsius during the course of a lunar day/night cycle. A complete lunar day, one full rotation about its axis, requires approximately 27-1/3 terrestrial days.

Compared to the Earth, the Moon is geologically inactive. Volcanism and internally generated seismic activity are almost nonexistent. Furthermore, water and atmospheric processes are unknown on the Moon. Other than igneous differentiation, which occurred early in lunar history, the main geological process that has acted on the Moon is impact cratering.

The Moon was heavily bombarded by meteoroids throughout much of its early existence. Evidence from the Apollo expeditions suggests that the bombardment decreased significantly about 3.8 billion years ago. This early bombardment and subsequent impacts during the past 3.8 billion years have pulverized the lunar surface into dust and small fragments of rock, a layer referred to as the lunar "regolith." The majority of the Moon's surface is made up of heavily cratered terrain, rich in the mineral plagioclase feldspar and known as the lunar "highlands." The uncompacted, upper portion of the highlands' regolith is 10 to 20 meters deep in most places. A smaller portion of the lunar surface, mostly on the Earth-facing side, consists of basaltic lava flows and is known as the lunar "maria." The maria are geologically younger than the highlands and thus have been cratered far less than the highlands have. The depth of uncompacted

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Space Life Sciences Symposium: Three Decades of Life Science Research in Space. 1987. Washington, DC: NASA Headquarters.

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regolith in the maria is roughly 4 to 5 meters.

The bulk density of lunar regolith increases with depth. Its upper surface is believed to have 45-percent porosity (Taylor 1982, p. 119). The porous upper 20 cm of the regolith results from repeated meteoroid impacts, which stir up the exposed surface and occasionally form large craters. These meteoroids represent potential hazards to both manned and unmanned activities. The meteoroid hazard on the lunar surface may be greater than that in free space (Mansfield 1971, p. 1-4-14). In addition to the free-space flux of meteoroids, there is also ejecta from the impacts. Some fragments of ejecta could have larger masses and slower velocities than the free-space population of meteoroids.

The Moon's surface is exposed to three types of hazardous ionizing radiation. The first two, the solar wind and solar flares, are produced by the Sun. The third type has its origin outside the solar system and is known as galactic cosmic rays.

The solar wind is an isotropically distributed, neutral plasma travelling at an average velocity of 400 km/sec. In Earth/Moon space, it has an average density of about 10 particles per cubic centimeter (Taylor 1982, p. 155). This plasma is composed of a relatively constant flux of charged particles, mainly electrons and protons, plus ions of various elements.

A solar flare is similar in composition to the solar wind, but its individual particles possess higher energies. A solar flare may be considered a transient perturbation in the solar wind. Exact timing of the occurrence of a flare is difficult to predict, but the frequency of flares may be related to the 11-year solar cycle. Most flares can be observed at the Sun's surface some time before a large increase in the solar wind's higher energy particles is detected in the vicinity of the Moon. Not all solar flares yield particles that reach the Earth/Moon vicinity, but, of those which do, this flux reaches a peak within hours and then decreases over several days to the previous solar wind level.

Galactic cosmic rays are apparently isotropically produced outside the solar system. The average cosmic ray flux has been almost constant over the past 50 million years (Taylor 1982, p. 159). Cosmic rays are made up of very high energy particles consisting mostly of protons and electrons, plus some heavy nuclei (iron, for example), positrons, and gamma rays. Both the Earth and the Moon are exposed to these cosmic rays, but the Moon's surface receives a higher intensity of cosmic rays than does the Earth's surface. The Earth's magnetic field and atmosphere provide significant protection, lacking on the Moon. The cosmic ray flux per square centimeter of lunar surface per year (during minimum solar activity) contains 1.29×10^8 protons plus 1.24×10^7 helium nuclei plus 1.39×10^6 heavier ions for a total of 1.4279×10^8 particles per cm^2 per year.* Fortunately, as the energy of the radiation increases from solar wind to cosmic rays, the frequency of encountering that radiation decreases.

*Counting only particles with a velocity greater than 10 MeV per nucleon. Information from D. Stuart Nachtwey, Medical Sciences Division, Lyndon B. Johnson Space Center, Houston.

Lunar Public Works

The dry, barren Moon might not seem like a promising land for settlement. But, with the eyes of a chemist, a pioneer settler may see lunar conditions as advantages and lunar soil as a bountiful resource.

Lunar Water Works

The first concern of a lunar pioneer must be water. There may or may not be water, as trapped ice, at the lunar poles, but there certainly is an abundance of its chemical components, oxygen and hydrogen. Oxygen is the most abundant chemical element (45% by weight) in the lunar soils, from which it may be extracted by various processes. In contrast, the concentration of hydrogen in lunar soil is very low, but the total quantity available is nevertheless great. The lunar surface has been bathed for billions of years in the solar wind, a flux of ionized atoms from the exterior of the Sun. These ions embed themselves in the surface of grains of lunar topsoil. Furthermore, meteorites, unimpeded by an atmosphere, continually plow under the old solar-wind-rich grains and expose new grains. In this way, large amounts of hydrogen have become buried in the soil, enough to produce (if combined with lunar oxygen) about 1 million gallons (3.8 million liters) of water per square mile (2.6 km^2) of soil to a depth of 2 yards (1.8 m). This hydrogen can be extracted by heating the soil to about 700°C. Supplying the Lunar Water Works is a matter of technology and economics, but not a matter of availability of oxygen and hydrogen on the Moon.

Lunar Community Farm

The next concern of a lunar pioneer will be food. Like hydrogen, carbon and nitrogen are available in large quantities from the lunar soil, although they are present in very low concentrations, having been placed there, like hydrogen, by the solar wind. All the other nutrients necessary to life are likewise present in the soil. Pioneer settlers should be able to obtain these elements by heating the soil. Once people have provided them with lunar water, carbon dioxide, oxygen, and nitrogen, plants should be able to extract nutrients directly from the lunar soil.

Lunar Filling Station

The lunar covered wagon will be a chemical rocket, its horsepower hydrogen and oxygen. Hauling these propellants from Earth will be expensive. It may prove cheaper to provide them from the lunar soil. Forty tonnes of hydrogen, a reasonable estimate of the amount needed for all transportation from low Earth orbit for a year, could be obtained from just 0.3 km^2 of soil mined to a depth of 1 m. Alternatively, lunar transport vehicles might burn a metal such as iron, aluminum, or silicon, even though these are less efficient rocket fuels than hydrogen. All three are major constituents of lunar soils, in chemical combination with oxygen, from which they can be extracted. In fact, each is a byproduct of one or more processes for producing oxygen. [Several techniques for extracting oxygen from lunar soils are proposed in the Materials *volume of this* Space Resources *report.]*

Lunar Lumberyard

Better than burning the iron, aluminum, and silicon produced as byproducts of oxygen extraction from lunar soils might be to use them to construct lunar shelters. Iron and aluminum can be fabricated into beams. The boards of space construction may well be made of glass. Molten lunar soil can be cast into silicate sheets or spun into fiberglass. These may have greater strength than similar products on Earth because of the lack of water to interfere with their polymer bonds. Partially distilled in a solar furnace, soil residue may take on the composition of a good cement, which when combined with locally produced water and the abundance of aggregate would become concrete. [These manufacturing processes are also discussed in the accompanying Materials *volume.] The unprocessed soil itself can serve as shielding against the diurnal temperature fluctuations and, more importantly, against the hazards of radiation unscreened by an atmosphere and undeflected by a magnetic field, as discussed by Rob Lewis in this paper.*

Lunar Light and Power

The Sun shines on the Moon plentifully and predictably, but only half the time. Storing solar energy over the 2-week-long lunar night seems difficult and may have to be done in the form of hydrogen, metals, and oxygen whose extraction was powered by energy from the Sun. Thus, initially, lunar power is likely to come from an imported nuclear power plant. But electrical power derived from the Sun is a likely lunar product and may even be the first major export to the Earth from the Moon (once the souvenir market has been satisfied). Eventually, the solar cells will probably be derived from lunar silicon, a byproduct of oxygen extraction, or from lunar ilmenite, recently shown to be photovoltaic. Conversion need not be efficient if a local material, simply obtained, is used as the photovoltaic. More futuristically, lunar helium-3 has been proposed for use as a fusion fuel superior to tritium in that it is not radioactive, does not have to be made in nuclear fission reactors, and yields a proton instead of a more destructive neutron when it fuses with deuterium.

Lunar soil contains in abundance the materials required for life support, transportation, construction, and power. With proper understanding and new ideas, lunar pioneers should be able to turn the lunar environment to their advantage.

Taken from Larry A. Haskin and Russell O. Colson, 1990, Lunar Resources—Toward Living Off the Lunar Land, in Proc. 1st Symp. NASA/Univ. of Arizona Space Engineering Research Center (in press), ed. Terry Triffet (Tucson).

The Human Factor

In order to develop permanent human settlements on the Moon, we must understand how the local environment influences the settlers' safety and health. The lack of atmosphere and the extreme temperature range mandate the use of sealed and thermally insulated enclosures. These enclosures—the colonists' first line of defense—will range from individual space suits to buildings. The next line of defense must protect the colonists from both meteoroids and radiation.

Meteoroid impacts may have effects ranging from long-term erosion of the surface materials of pressure vessels and space suits all the way to penetration and subsequent loss of pressure and injury to personnel (see fig. 9). More serious impacts could result in destruction of equipment and loss of life.

Figure 9

Crisis at the Lunar Base

A projectile has penetrated the roof of one of the lunar base modules and the air is rapidly escaping. Three workers are trying to get into an emergency safe room, which can be independently pressurized with air. Two people in an adjoining room prepare to rescue their fellow workers. The remains of the projectile can be seen on the floor of the room. This projectile is probably a lunar rock ejected by a meteorite impact several kilometers from the base. A primary meteorite would likely be completely melted or vaporized by its high-velocity impact into the module, but a secondary lunar projectile would likely be going slowly enough that some of it would remain intact after penetrating the roof. Detailed safety studies are necessary to determine whether such a meteorite strike (or hardware failure or human error) is likely to create a loss-of-pressure emergency that must be allowed for in lunar base design.

Artist: Pamela Lee


CAPACITY 3
SAFE ROOM
EMERGENCY
WARNING
OXY PRESS
TEMP CO2

In 1971, the Rockwell Lunar Base Synthesis Study investigated several strategies for dealing with the meteoroid hazard. They took a probabilistic approach to the problem of safety and examined several options. Rockwell was interested in providing portable shielding for short-term surface activities as well as more permanent fixed shielding. The shielding might be needed many times during an expedition covering large distances.

On Earth, mobile expeditions which require temporary environmental protection that is lightweight and easy to redeploy often use tents. The Rockwell study examined the use of a tent-like structure which could be erected over an inhabited pressure vessel. The tent could be constructed of a lightweight material such as aluminum foil or nylon. The Rockwell investigators anticipated that such a structure would act as an extra outer layer of protection against meteoroid impact. For their calculations, the tent had an area of 46 m^2 and the insulated wall of the pressure vessel had a density of approximately 8 kg/m^3. A small gap between the tent and pressure wall was initially considered. This arrangement could provide a 0.9999 probability of no penetrations in 100 days if only a free-space meteoroid flux was assumed. However, assuming also the secondary ejecta hazard, they found that the tent system had only a 0.1 probability of not being penetrated within 100 days. A logical next step would be to add more layers of material to the tent. This, of course, increases the weight of the tent and its associated transportation costs.

The next option that Rockwell considered was identical to that just described but with an additional layer of material filling the gap. In theory, the tent would serve to fragment a meteoroid and the underlying material would impede and absorb the fragments before they reached the pressure vessel. On the basis of their surface meteoroid flux model, the gap filler would need to have a density of 16 kg/m^3 to provide a 0.9999 probability of no penetration within 100 days. A design of this type may prove to be practical as portable meteoroid shielding for short-term surface activities.

However, these measures would be completely inadequate for any long-duration habitat (for a stay of over 100 days), so the addition of shielding material seemed desirable. If lunar regolith were used as a gap filler, significant protection could be added without increasing transport costs from Earth. Rockwell concluded that a gap of approximately 15.2 cm (6 inches), filled with lunar regolith, would reduce the penetration risk to less than one chance in 10 000 over a 2- to 5-year stay.

Although meteoroid impacts may be a serious problem on an infrequent basis, the effect of ionizing radiation on human health is continuous and cumulative over an individual's lifetime. A brief discussion of radiation dosimetry is now in order. The fundamental unit of radiation transfer is the *rad*; 1 rad represents the deposition of 100 ergs of energy in 1 gram of mass. The characteristics of the deposition mechanisms vary and additional factors must be considered. One conversion factor is the quality factor, Q, which is conservatively based on the experimentally determined relative biological effectiveness, RBE. When Q is multiplied by the rad exposure, the result is a unit of dosage corrected for the type of radiation; this resulting dosage is measured in a unit known as the *rem*.

Individual responses to radiation exposure vary somewhat and there is controversy over safe limits for long-term, low-level exposures. Currently, the maximum permissible whole-body dose for radiation workers is 5 rem/year and for the general public 0.5 rem/year (CRC Handbook of Tables for Applied Engineering Science 1980, p. 753). Both of these doses are larger than the dose of background radiation at sea level that humans are normally exposed to. Just as radiation workers must accept a greater risk than do members of the general public, so astronauts are prepared to accept a greater risk than radiation workers. Table 3, provided by Stu Nachtwey, lists the doses and health risks that the Medical Sciences Division at the Johnson Space Center estimates an astronaut on a Mars or lunar base mission would be exposed to during a period of minimum solar activity.

TABLE 3. *Approximate Radiation Doses and Health Risks for an Astronaut on a Mars or Lunar Base Mission During Minimum Solar Activity*
[From D. Stuart Nachtwey, Johnson Space Center]

Radiation source	Representative shielding	Skin dose equivalent	Deep organ (5 cm) dose equivalent	Excess lifetime cancer incidence in a 35-year-old male*
Chronic exposure				
Trapped belts (one-way transit)	2 g/cm^2 Al	< 2 rem	< 2 rem	< 0.1%
Free space	4 g/cm^2 Al	75 rem/yr	53 rem/yr	~ 1.2%/yr of exposure
On lunar surface	4 g/cm^2 Al	38 rem/yr	27 rem/yr	~ 0.6%/yr of exposure
On martian surface	16 g/cm^2 CO_2 (atm.)	13.2 rem/yr	12 rem/yr	~ 0.3%/yr of exposure
Acute exposure to large (e.g., Aug. '72) solar particle event				
Free space	2 g/cm^2 Al	1900 rem	254 rem	~ 5.7%
On lunar surface	4 g/cm^2 Al	440 rem	80 rem	~ 1.8%
+ shielding	15 g/cm^2 Al	19 rem	9 rem	~ 0.2%
On martian surface	16 g/cm^2 CO_2 (atm.)	9 rem	4.6 rem	~ 0.1%
+ shielding	60 g/cm^2 Al	< 1 rem	< 1 rem	< 0.03%

*The excess cancer incidence for a 35-year-old female is roughly twice that for a 35-year-old male.

The rate of irradiation per unit time and the age and sex of the individual at irradiation are also important. Younger people are more sensitive to the cancer-inducing effects of radiation than older people, and females are more sensitive than males because of cancer induction to the breast and thyroid. Other serious radiation effects include cataracts, genetic damage, and death. Radiation exposure is considered cumulative over an individual's lifetime.

Solar flares and cosmic rays are the most dangerous radiation events that lunar pioneers will be exposed to. The cosmic ray dosage at the lunar surface is about 30 rem/year and, over an 11-year solar cycle, solar flare particles with energies greater than 30 MeV can deliver 1000 rem (Silberberg et al. 1985). Solar flares deliver most of their energy periodically during only a few days out of an 11-year cycle; whereas, the cosmic ray flux is constant.

Although the lunar surface radiation flux is too high to spend much time in, it is definitely possible to alleviate the radiation danger with shielding. When colonists are removed from continuous exposure to surface radiation, long-term settlement becomes possible. As in the case of meteoroid protection, the simplest solution is to use locally available regolith for bulk shielding of habitats.

Silberberg et al. (1985) have suggested that a compacted layer of lunar regolith at least 2 meters thick should be placed over permanent habitats. With shielding of this thickness, the colonists' yearly exposure could be held to 5 rem per year if they spent no more than 20 percent of each Earth month on the surface. In order to provide an overall level of protection of no more than 5 rem per year even in the event of an extreme solar flare, such as occurred in February 1956, the depth of shielding would have to be doubled.

For the sake of completeness, it should be pointed out that some lunar regoliths contain a naturally radioactive component material known as KREEP. KREEP, probably a product of volcanism, contains radioactive potassium, uranium, and thorium. Material containing a high concentration of KREEP should not be used for shielding, and care should be taken to avoid concentrating it as shielding is prepared. The concentration of KREEP in most regolith material would add an amount of radioactivity no more than that in the granite used in buildings here on Earth. If the small contribution by KREEP to radiation dose is considered when exposures are calculated, it should not pose any significant health problem by itself.

It is a well-known fact that cosmic rays produce secondary particles, such as neutrons, upon collision with matter. These byproducts can add to the radiation exposure if the shielding is not "thick" enough to absorb the secondary neutrons as well. It turns out that the 15.2-cm-thick layer of compacted regolith proposed earlier for a meteoroid shield is not optimum. Obviously, if "thin" shielding is to be used, its utility must be examined in light of its disadvantages.

It seems likely that the initial lunar base will be constructed of modified space station modules, Space Shuttle external tanks, or similar pressure vessels. These pressure vessels will be transported to the lunar surface and placed in excavations. Once the modules are in place, they will be covered with the previously excavated regolith to provide shielding (see fig. 10). Land (1985) describes various approaches and consequences to providing support for the shielding above the pressurized enclosures. Logistically and structurally the use of bulk regolith is a convenient solution. Its use reduces the need to transport mass out of the Earth's gravity well and favors the transport of sophisticated value-added mass instead. Eventually, as the settlement begins to grow and develop industrial capability, locally available metals, glass, and bulk regolith can be fabricated into new facilities.

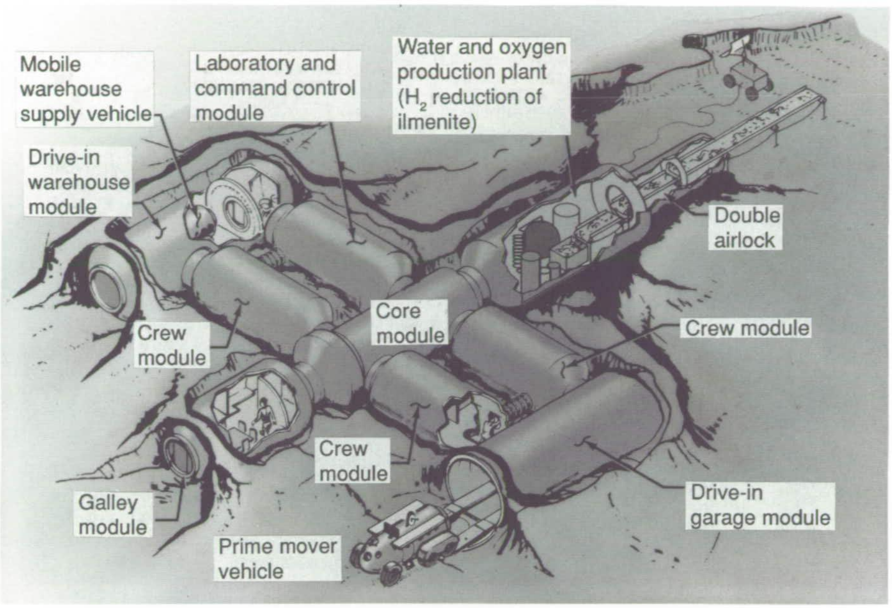


Figure 10

Lunar Base Modular Configuration

Initial base components could be made up of modified space station modules. The frontispiece shows how such modules might look in the panorama of a lunar base.

The advantage of using modified space station modules is that they will already have been designed, tested, and fabricated for use in space. The disadvantage is that a module designed for zero gravity and free space exposure might require major changes to fit the lunar environment with 1/6 g, ubiquitous dust, and the weight of piled-on regolith shielding.

Because of the nature of the lunar environment, much of the pioneers' time will be spent underground within their habitat modules. For safety and convenience, these modules will be linked together with tunnels (see fig. 11). While this underground environment will be different from Earth's standard, it need not be unpleasant or confining. By the time the base is under construction, manned operations on the space station will have provided a lot of useful experience in human factors engineering. Laboratories, factories, farms, and entertainment facilities will all be integrated into the underground installations on the Moon (see fig. 12). Some types of storage will also be underground, but a number of facilities will remain above ground.

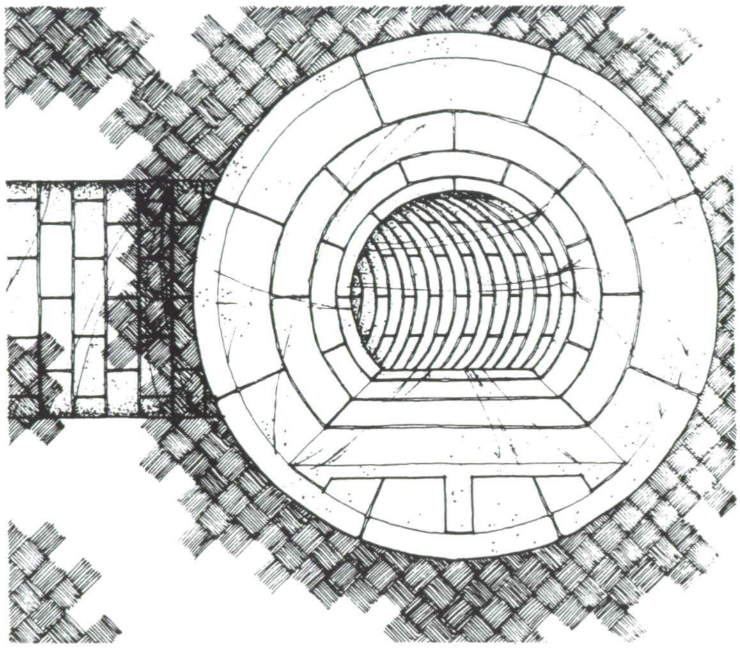


Figure 11

Shielded Tunnels

The modules of a lunar base would be connected by tunnels, naturally shielded from surface hazards. The tunnels could be made airtight for use but would likely also be provided with airlocks for safety in case of depressurization.

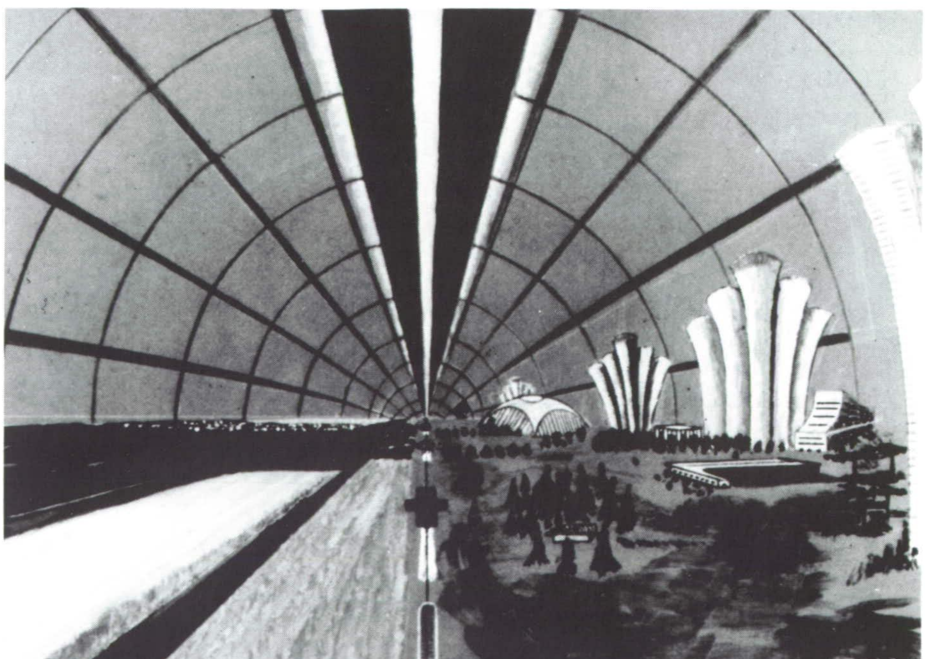


Figure 12

An Agricultural Zone in Krafft Ehricke's Selenopolis

Although the initial lunar outpost would no doubt be quite spartan, the expanding lunar base could be modified to make life under the lunar surface quite Earthlike and pleasant.

Transportation facilities such as hangars, landing pads, and refueling stations will be located on the lunar surface (see fig. 13). Power plants and communications superstructure will be surface installations as well. Some storage will be in surface warehouses (see fig. 14).

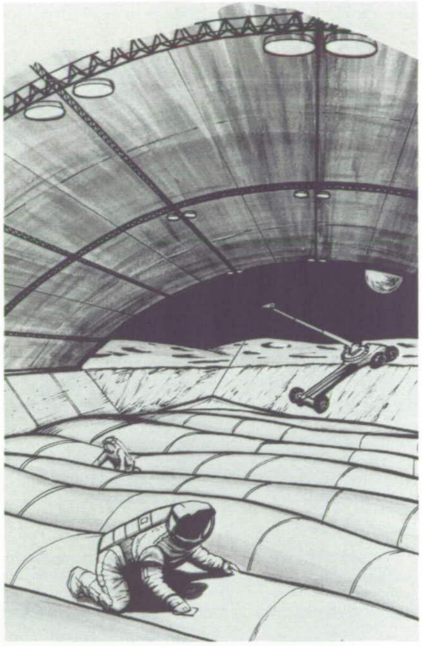


Figure 13

Lunar Hangars

Mobile surface equipment will need to be stored in protective hangars. Such hangars would provide shade against the Sun's heat during the 2-week-long lunar day and lighting for work during the equally long lunar night.

Artist: Pat Rawlings

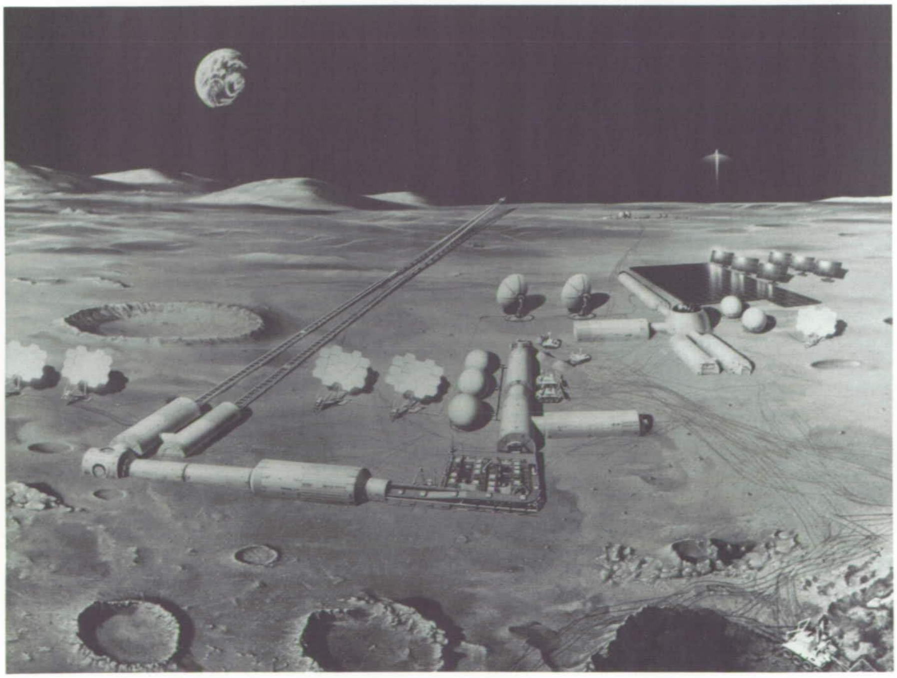


Figure 14

Lunar Surface Activities

Activities such as mining, transport, and processing will almost by necessity be conducted on the surface. While automation and teleoperation will be used extensively, some minimum amount of human tending will always be required. In this particular concept (from NASDA, the Japanese space agency), a processing plant produces oxygen and metals and an electromagnetic mass driver shoots these products into lunar orbit, where they can be used to support Earth-Moon space activities.

Strategies for Surface Operations

Although space suits appropriate to the lunar environment were successfully used during the Apollo missions, they are not the only means of conducting surface activities. Moon suits have several disadvantages, one problem being their limited duty cycle. Consumables, recycling systems, and operator fatigue are the most obvious limitations to how long a "moon walk" can last. The Apollo 14 astronauts walked everywhere and averaged about 4-1/2 hours per moon walk. By contrast, the Apollo 17 astronauts' surface activities, augmented by their use of the lunar roving vehicle (see fig. 15), averaged about 8 hours. Another constraint due to moon suit use is the time it takes to dress and undress (see fig. 16) and repair and refurbish the suits. Plenty of spare parts will probably be required. However, these difficulties are minor annoyances. The most serious problem with exclusive use of moon suits for surface activities is their insufficient meteoroid and radiation protection.

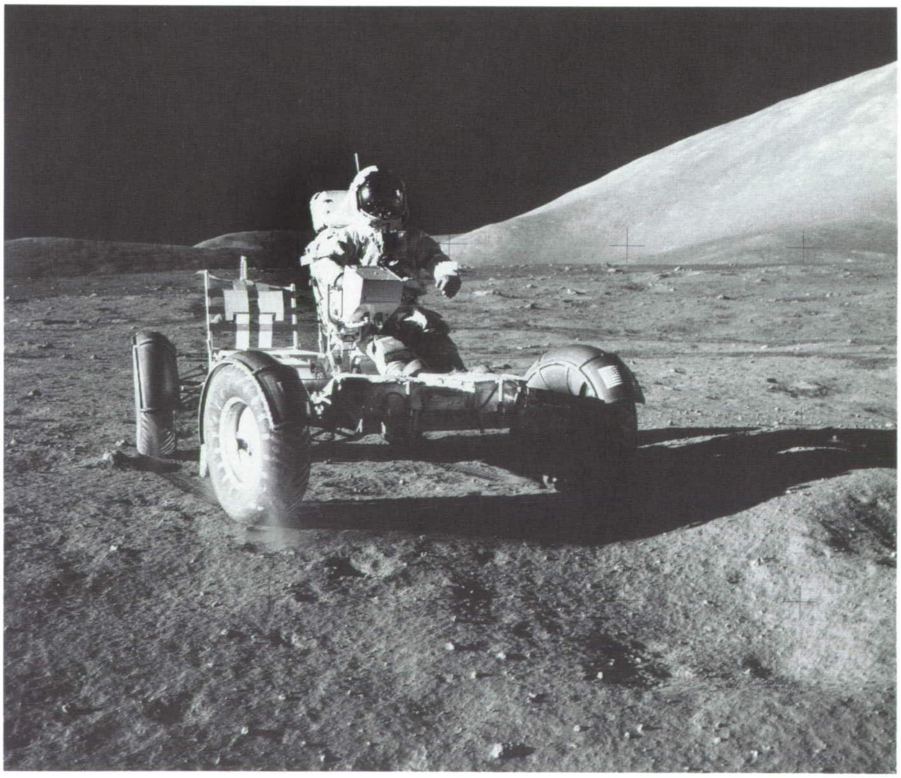


Figure 15

Lunar Rover

The use of the Apollo lunar Rover greatly increased the lunar explorers' effectiveness. Mobility will also be very desirable in lunar base operations and will be especially important for scientific exploration.

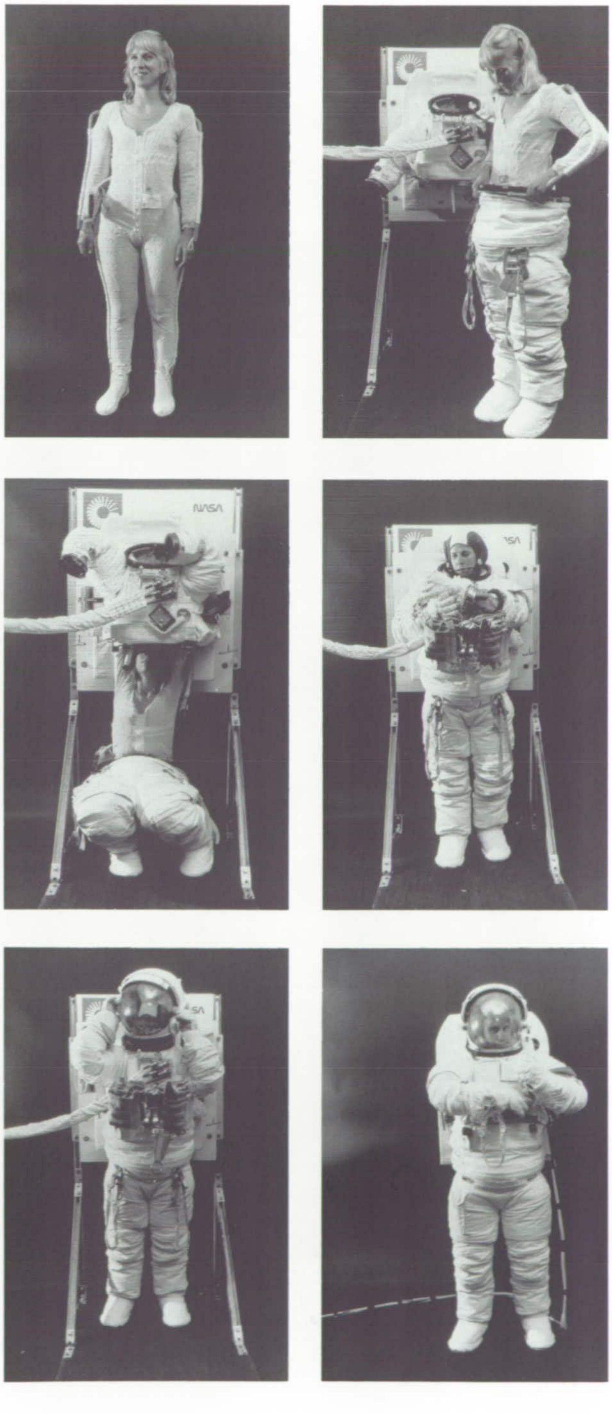
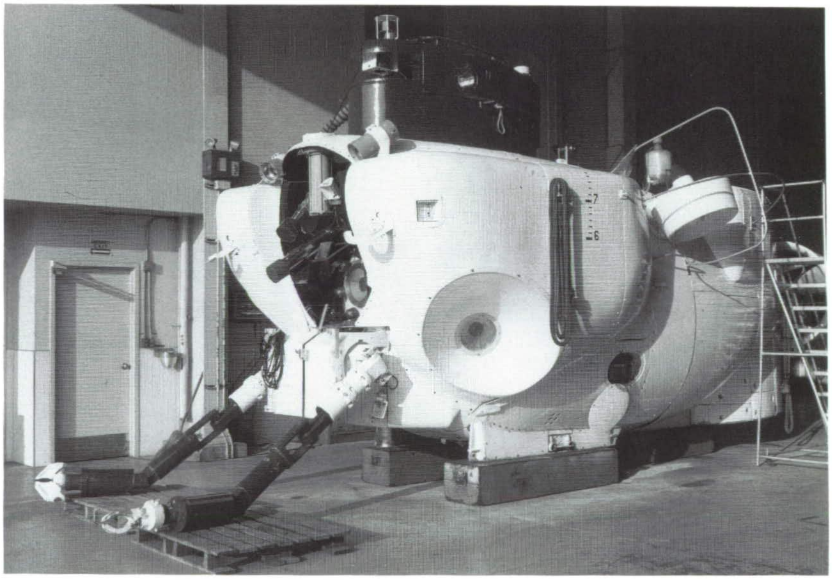


Figure 16

Suiting Up

Much time is consumed donning or doffing a space suit.

Therefore, the development of pressurized surface vehicles equipped with external tools and manipulators is desirable (see fig. 17). These vehicles would be analogous to the specialized submarines used for exploration, research, and repair in the Earth's oceans. Such devices provide their operators with a safe environment and permit access to a more hazardous one.



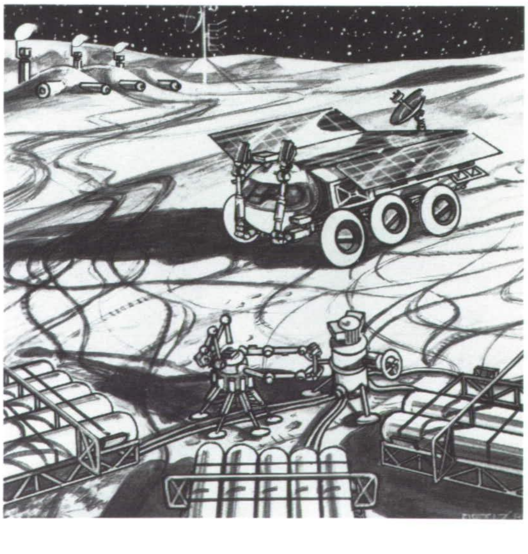


Figure 17

Vehicles for Operations in Hostile Environments

"Alvin" deep-diving research submarines protect their crews from the hostile ocean environment while permitting mobility and interaction within it. Cameras, floodlights, and portholes enhance the crew's visual access to their surroundings, and specialized manipulators and end effectors allow physical interaction. Inside the submarine, the crew is maintained in a shirt-sleeve environment. It seems highly likely that pressurized surface vehicles equipped with external tools will be developed to meet similar needs on the lunar surface.

If vehicles of this type were developed for use on the Moon, they would definitely have to provide meteoroid protection and the radiation protection necessary to keep the occupants' exposure well within the 50 rem/year limit [to the blood-forming organs (NCRP Report No. 98, July 31, 1989, p. 164)]. A thick layer of compacted regolith built into the hull may serve this purpose.

Another way to reduce radiation exposure problems might be to permit only older personnel (volunteers over 35 and people who have already had children) to spend much time on the surface and keep the younger personnel underground. This idea is based on the premise that delayed reactions to irradiation, like cancer, take long enough to develop that older people who are exposed may die of natural causes before the reaction occurs. However, this seems to be a solution of minimal merit. Every colonist will require an individual radiation dosimetry record and a "weather" forecast concerning the solar flare hazard whenever he or she leaves the habitat.

A truly satisfactory solution appears possible. Taking the manned vehicle concept one step further reveals another type of device, the teleoperated robot, which is well suited to the lunar environment. A teleoperated robot is a remotely controlled device which may be used to provide a human presence in a hazardous environment. Typically, the human operator directly controls the activities of the robot and receives feedback from it, so it is an electronic and mechanical extension of the person, essentially a surrogate body. Teleoperated robots have been used in the nuclear industry for years; they are finding applications in underwater work at great depths; and they have seen limited application in space.

Lunar teleoperators, like the ones shown in figure 18, could be operated in one of two modes: directly from the lunar habitat, as in figure 19, or indirectly from a space station or a facility on Earth. Each mode has its unique characteristics. Operation from Earth would be slower because of the several-second, round-trip radio signal delay. In this case, the teleoperated device may require built-in reflexes to protect itself, if the most recent command from Earth is in conflict with current local conditions. An example of this would be having the teleoperated device stop before walking or driving over the edge of a cliff which has just appeared on the operator's TV screen on Earth. In the early 1970s, the Russians successfully demonstrated the usefulness of their Lunokhod teleoperated roving vehicles on the Moon (see fig. 20).

It has been commonly thought that the main problem faced by Earth-based operators who "commute" to work on the Moon by radio would be severe fatigue and frustration due to the timelag. To evaluate this possibility, I conducted a series of lunar-time-delay manipulation and mobility experiments using a mobile robot equipped with a 4-degree-of-freedom manipulator arm (see fig. 21). My results (1989) indicate that the 3-sec delay inherent in round-trip communication between the Earth and the Moon is not a significant barrier to teleoperated manipulation and mobility. With proper system design, this mode of operation will, at worst, require patient people and predictive positioning aids.

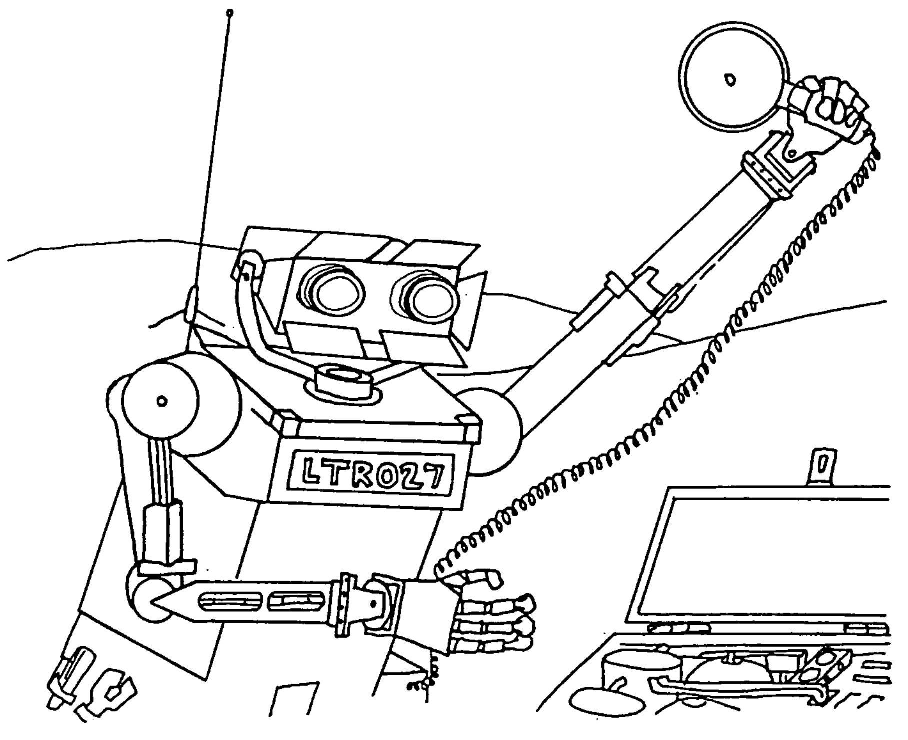


Figure 18

Teleoperated Robot

Teleoperated robots will be designed to provide a human presence on the lunar surface. This robot's arms have the same freedom of movement as human arms: three degrees at the shoulder, one at the elbow, and three at the wrist. Its hands are modeled on human hands but require only three fingers and a thumb. The robot's head can turn up and down, right and left. It has two TV cameras for stereo vision (with glare shades, which are movable on hinges).

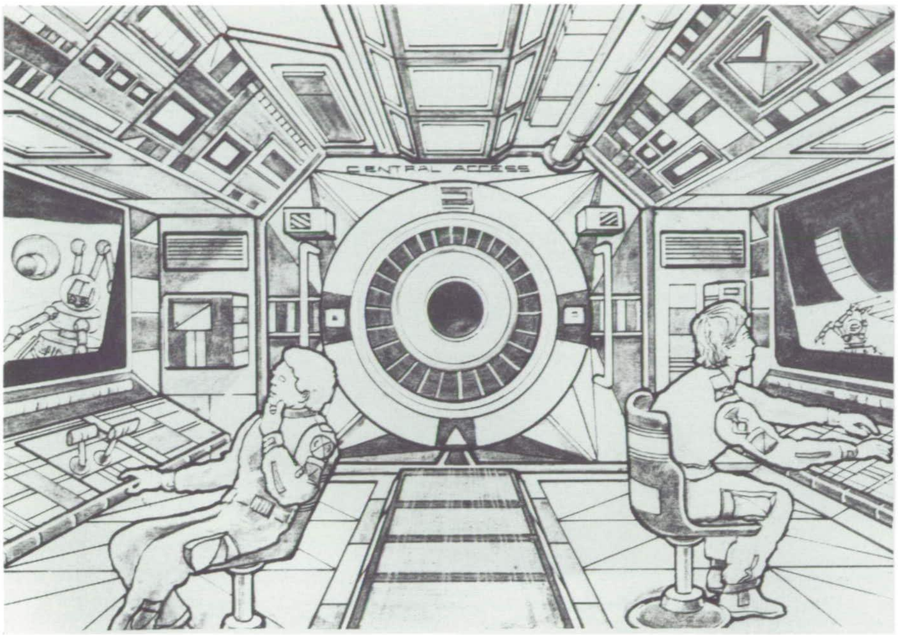


Figure 19

Teleoperations Control Center Underground at the Lunar Base

Surface activities could easily be directed from comfortable underground facilities. Such control centers would provide safe environments for lunar workers who would otherwise be required to do routine jobs in a hazardous environment. Each operator could supervise the activities of many semi-autonomous robots or directly control one telerobot to apply more specialized skills to the task at hand. Although the two human operators shown are controlling and monitoring telerobotic equipment at two different locations, they could just as easily be coordinating their teleoperations. Such a team effort could even be assisted by additional controllers located at other sites on the Moon or elsewhere, as long as there were enough telerobots at the work site and sufficient communications channels. Keep in mind that the controllers would always have the option to shut down their telerobots temporarily so that they could take a personal break or attend immediately to another matter within the base without losing travel or space suit removal time or wasting limited excursion supplies like oxygen.

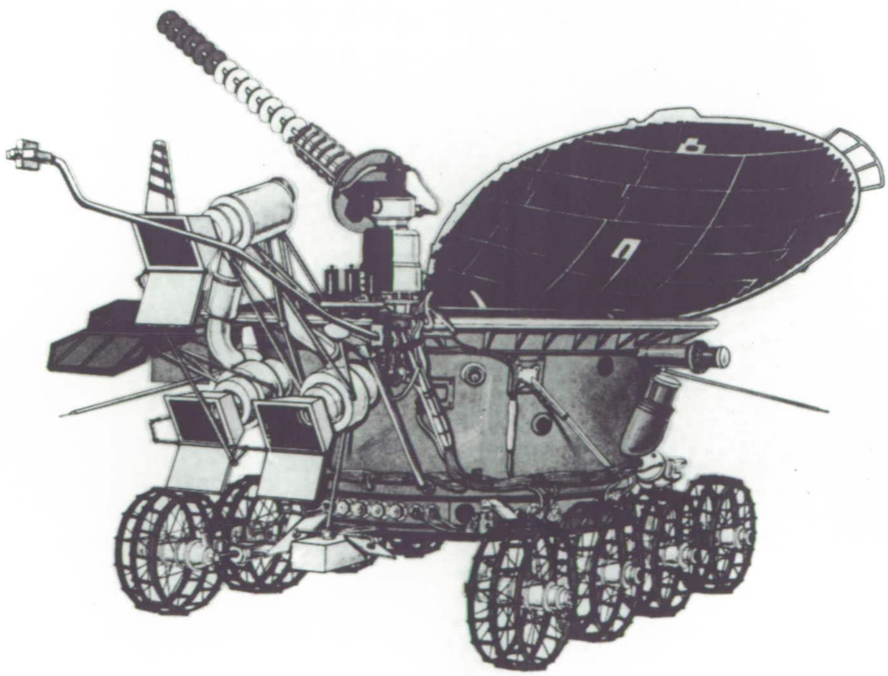


Figure 20

Lunokhod

Automated vehicles roving over another planetary body were first used in the early 1970s by the Soviets on their Lunokhod missions. These lunokhods were capable of traveling tens of kilometers at speeds up to 2 km/hr. They were run from a Soviet control center by a crew of five—commander, driver, navigator, operator, and onboard-systems engineer. The crew used slow-scan television images and systems readouts to drive and operate the vehicles.

Figure 21

SSI Teleoperations Simulation Chamber

The Space Studies Institute in Princeton, NJ, has been involved in a continuing experiment to evaluate the usefulness of time-delayed teleoperation under lunar conditions. Here the designers, Rob Lewis and David Brody, demonstrate a telerobotics facility to Jean-Loup Chrétien, who has been a guest cosmonaut. The facility consists of an operator control console and a simulated lunar environment chamber (with its side cover removed to reveal the interior). On the far right, a mobile robot equipped with a 4-degree-of-freedom manipulator can be seen interacting with a workstation while under the time-delayed control of the operator. Although the operator receives video from inside the chamber, direct visual access into it is not possible during experiment runs. The chamber has been optimized to visually replicate lunar conditions when viewed with video cameras.

Photo: Barbara Faughnan

Local use of teleoperated devices would not be hampered by time delays, but it would require additional relay stations, such as comsats or mountaintop repeaters, to overcome the obstacles to line-of-sight radio propagation on the lunar surface. It seems likely that teleoperated robots will be controlled from Earth, from the Moon, and from points in between.

Teleoperated robots will not replace people; rather they will enhance a person's capabilities. As mentioned earlier, the teleoperated robot may be controlled in a master-slave mode, given sufficient feedback to allow the human operator to sense and react to the robot's environment as if the person were there. Another control approach uses "supervised autonomy." Supervised autonomy involves a working partnership between a human, who sets goals and supervises their implementation, and a more fully automated robot, which is responsible for carrying out specific tasks. Much less feedback would be necessary using this strategy.

Sending a number of teleoperated machines to the Moon to prepare the way for later colonists may be warranted. This would have the twin advantages of maximizing safety and limiting the cost of the initial missions, as local materials could be used to prepare a base and supplies before the people moved in. Once the settlement was occupied, teleoperators controlled from Earth would act as "force multipliers." They could be run by several shifts of operators on Earth each day (including weekends). Thus, each machine could do the work of three or more lunar colonists, without the costs of bringing those colonists to the Moon and providing life support for them. In addition, teleoperated devices could potentially permit experts from Earth to provide timely services otherwise unavailable locally.

Teleoperated machines used in conjunction with a manned base could be regularly repaired and rebuilt by the lunar staff as required by changing needs. We should remember that teleoperated machines are far less sensitive to radiation than people and can be optimized for their environment and tasks. If a teleoperator is hit by a meteoroid, it may possibly be repaired or salvaged. If not, it certainly is more expendable than a person. Thus, the development of teleoperators for lunar surface use is definitely worth further investigation.

The Moon is an ideal "large" space station and offers many advantages over other near-Earth locations, such as natural gravity and useful resources. Extensive human activities on the Moon will be constrained initially by the lunar environment because it is so different from the Earth's. Means to ease these constraints are possible and should be pursued. There is much to be gained from a permanent human presence on the Moon.

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Summer Study Postscript: A 1986 Perspective

Philip R. Harris et al.

Now that the National Commission on Space has set out bold goals and strategies for the American space program in the next 50 years, how can we turn such visions into realities? Since the *Challenger* tragedy and other space failures have brought about a crisis of confidence in NASA, what innovations are necessary to rebuild public consensus and support? What initiatives can the private sector take to promote the peaceful use of space by its exploration and industrialization? The faculty fellows from the 1984 summer study propose three possibilities for action by NASA and supporters of the space program.

A National Lottery for Space Enterprises

Public lotteries to support exploration and civilizing ventures on new frontiers are part of the Nation's tradition. They were used by the English to support the Jamestown colonization and to open the western frontier. They have become popular again in this century as a means of raising money for state governments. Such a lottery could alleviate the national tax burden imposed by the plans of the National Commission on Space, which they estimate to cost $700 billion.

As a step to providing the vigorous leadership on the space frontier called for by these commissioners, either the Congress or a private consortium or a combination of public and private leaders might launch this national lottery. The first target would be to obtain funding for a fourth orbiter, to be devoted exclusively to scientific, commercial, and international use. Named "Challenger II," it would be a public memorial and expression of appreciation to the seven crewmembers who lost their lives in the first shuttle of that name. Once the Shuttle fleet was back to full capacity, the next objective might be funding for more advanced aerospace planes. Just as the Conestoga wagons and the railroad opened up new resources in the West, so will these initial vehicles on the space "highway."

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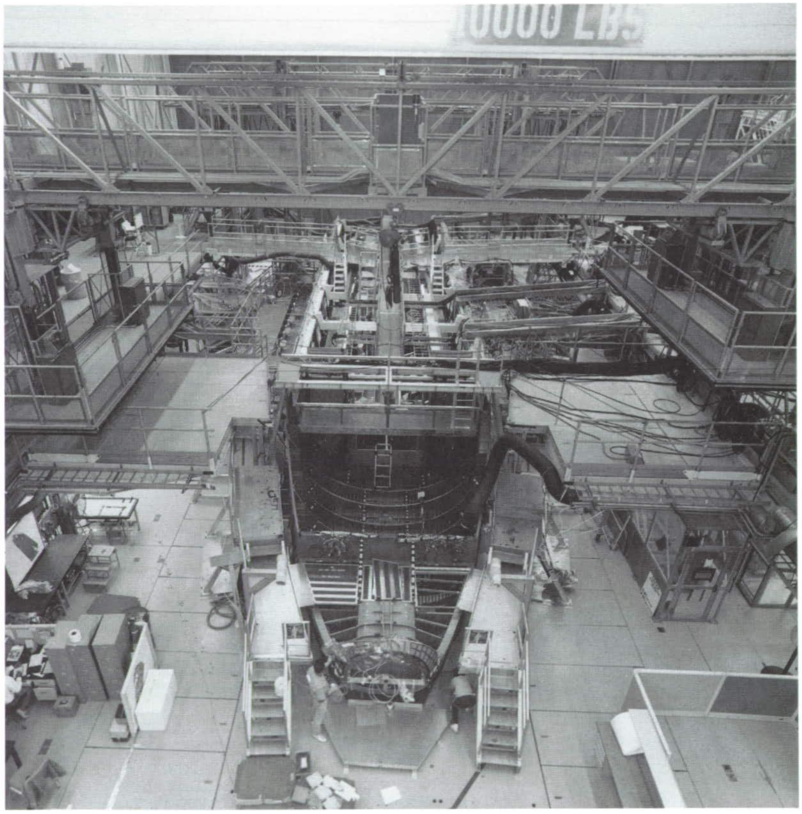


A Fourth Orbiter

The Endeavour, *expected to bring NASA's Shuttle fleet to four again, is seen under construction at Rockwell's manufacturing facility in California.*

Continued fundraising of this type would be designated to help underwrite the space infrastructure that will enable us to tap space resources (e.g., the construction of the space station and lunar or martian bases of operation).

How? As the National Commission on Space gathered its input, hundreds of individuals in 15 public forums contributed their ideas. Such people, along with the space advocacy groups, could provide the momentum for this National Lottery for Space Enterprises. At the present time, there are 50 groups advocating the development of space. They have a collective membership of 300 000 and an aggregate annual budget of $30.5 million. All these, together with other space business leaders and entrepreneurs, could provide the thrust to translate the lottery proposal into dollars for space enterprise. Readers of such magazines as *Aviation Week & Space Technology* and *Commercial Space* could be enlisted in such a campaign. Gradually, beginning with Canada, the lottery could be extended internationally. We suggest Lee Iacocca and his leadership of the campaign to restore the Statue of Liberty as an example of the type of citizen and strategy needed in this next national endeavor. "We the people of the United States of America" can implement the goals set forth by the National Commission on Space.

A White House Conference on Space Enterprise

Another step to encourage civilian leadership in the American space program would be a White House conference. Space planners and advocates should urge their congressional representatives to introduce a bill supporting such a convocation and calling upon the Administration to issue invitations and set an agenda. The primary purpose of the conference would be to examine ways to implement the recommendations of the National Commission on Space, thereby opening up the space frontier and improving the quality of life here on Earth. The secondary purpose would be to develop a national consensus on the peaceful and commercial exploration and utilization of space resources.

A White House Conference

The faculty fellows in this NASA summer study group urge that a White House conference be called to find ways and means to implement the recommendations of the National Commission on Space, thereby opening up the space frontier and improving the quality of life here on Earth.

Photo: Joyce C. Naltchayan

A call by the President to carry out the space commission's goals* would boost American morale, turn our energies outward, and ensure the country's space leadership into the 21st century. To recharge the national enthusiasm for space, distinguished Americans and other guests would be invited to this conference to propose immediate and pragmatic means for reaching the commission's targets. The planners might invite corporations in the space business to join the Government in sponsoring the event. The participants would include not only space professionals but also people of competence and distinction in positions to influence the citizenry in their support of space activities. We suggest Walter Cronkite as the type of person capable of communicating the message from such a White House conference and enlisting public support. The aim would be to obtain massive media attention not only to the conference but also to its results.

The proposed White House conference might be structured on a theme set forth by the National Commission: "Stimulating space enterprises for the direct benefit of the people on Earth." The sessions might be organized around the four parts of the commission's report—civilian space goals for 21st century America, low-cost access to the solar system, opening the space frontier in the next 20 years, American leadership on the space frontier in the next 50 years.

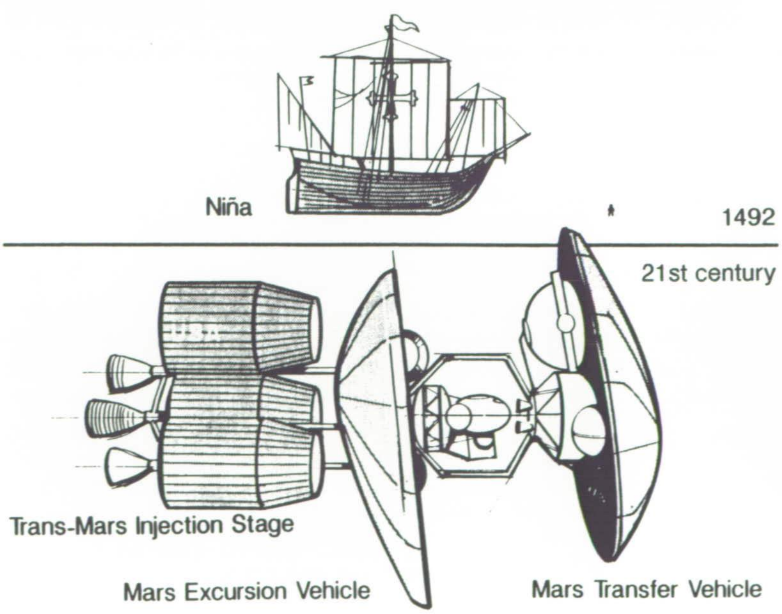
Reorganization of the National Aeronautics and Space Administration

If the goals and recommendations set forth by the National Commission on Space are to be achieved, then NASA needs to be renewed and reorganized. The internal renewal of its organizational culture and management is already under way as a result of the findings of the Presidential Commission on the Space Shuttle Challenger Accident. But reorganization in the charter and structure of the agency might enable it to become more free of the Federal bureaucracy, annual budget battles, and political pressures that undermine its ability to make strides in space.

*Such a call was issued by President George Bush in his July 20, 1989, speech on the steps of the Smithsonian Air and Space Museum. Specifically, he proposed commitment to three of the Commission's twelve technological milestones in space: Space Station *Freedom*, a permanent lunar outpost, and human exploration of Mars.

In 1984, the faculty fellows of the NASA summer study recommended that legislation be passed to strengthen NASA by making it more autonomous. (Models exist in the U.S. Postal Service, the Tennessee Valley Authority, and the New York Port Authority.) By creating a National Aeronautics and Space Authority as a semiautonomous corporation, our Nation's leaders would allow the NASA budget to be set for long-term project development. The funding for research and development could be separated from that for operations. Such legislative changes might enable NASA to enter into joint ventures with the private sector in the United States and abroad, as well as with other national space entities, so as to supplement its income beyond Government appropriations. Then, creative financing of space ventures might be discovered through the issuance of bonds or the sale of stock in limited R&D partnerships or in space trading companies. (Shades of the Dutch East India Company!) Because of the scope and complexity of space development, NASA needs to be empowered to give leadership in promoting the cooperative efforts of Government, universities, and industry in the furtherance of human enterprise in space.

Ships of Exploration



Shipsof Exploration

"From the voyages of Columbus to the Oregon Trail to the journey to the Moon itself, history proves that we have never lost by pressing the limits of our frontiers," said President George Bush on the 20th anniversary of the Apollo 11 landing on the Moon. The President urged that we press the limits of our frontiers on to another planet and make a journey to Mars.

Our Niña (and Pinta and Santa Maria) might look like this: A trans-Mars injection stage, essentially large propellant tanks with rocket motors attached (Columbus' ships didn't have to carry their propellant), to propel the ship from Earth to Mars. A Mars excursion vehicle, with its aerobrake to slow the descent into Mars orbit (we, too, will make use of the "wind") and its martian lander. And a Mars transfer vehicle, also equipped with an aerobrake and much smaller rocket motors, to enter Mars orbit and bring the crew home.

Addendum: Participants

The managers of the 1984 summer study were

David S. McKay, Summer Study Co-Director and Workshop Manager
Lyndon B. Johnson Space Center

Stewart Nozette, Summer Study Co-Director
California Space Institute

James Arnold, Director
of the California Space Institute

Stanley R. Sadin, Summer Study Sponsor
for the Office of Aeronautics and Space Technology
NASA Headquarters

Those who participated in the 10-week summer study as faculty fellows were the following:

James D. Burke	Jet Propulsion Laboratory
James L. Carter	University of Texas, Dallas
David R. Criswell	California Space Institute
Carolyn Dry	Virginia Polytechnic Institute
Rocco Fazzolare	University of Arizona
Tom W. Fogwell	Texas A & M University
Michael J. Gaffey	Rensselaer Polytechnic Institute
Nathan C. Goldman	University of Texas, Austin
Philip R. Harris	California Space Institute
Karl R. Johansson	North Texas State University
Elbert A. King	University of Houston, University Park
Jesa Kreiner	California State University, Fullerton
John S. Lewis	University of Arizona
Robert H. Lewis	Washington University, St. Louis
William Lewis	Clemson University
James Grier Miller	University of California, Los Angeles
Sankar Sastri	New York City Technical College
Michele Small	California Space Institute

Participants in the 1-week workshops included the following:

Constance F. Acton	Bechtel Power Corp.
William N. Agosto	Lunar Industries, Inc.
A. Edward Bence	Exxon Mineral Company
Edward Bock	General Dynamics
David F. Bowersox	Los Alamos National Laboratory
Henry W. Brandhorst, Jr.	NASA Lewis Research Center
David Buden	NASA Headquarters
Edmund J. Conway	NASA Langley Research Center
Gene Corley	Portland Cement Association
Hubert Davis	Eagle Engineering
Michael B. Duke	NASA Johnson Space Center
Charles H. Eldred	NASA Langley Research Center
Greg Fawkes	Pegasus Software
Ben R. Finney	University of Hawaii
Philip W. Garrison	Jet Propulsion Laboratory
Richard E. Gertsch	Colorado School of Mines
Mark Giampapa	University of Arizona
Charles E. Glass	University of Arizona
Charles L. Gould	Rockwell International
Joel S. Greenberg	Princeton Synergetics, Inc.
Larry A. Haskin	Washington University, St. Louis
Abe Hertzberg	University of Washington
Walter J. Hickel	Yukon Pacific
Christian W. Knudsen	Carbotek, Inc.
Eugene Konecci	University of Texas, Austin
George Kozmetsky	University of Texas, Austin
John Landis	Stone & Webster Engineering Corp.
T. D. Lin	Construction Technology Laboratories
John M. Logsdon	George Washington University
Ronald Maehl	RCA Astro-Electronics
Thomas T. Meek	Los Alamos National Laboratory
Wendell W. Mendell	NASA Johnson Space Center
George Mueller	Consultant
Kathleen J. Murphy	Consultant
Barney B. Roberts	NASA Johnson Space Center
Sanders D. Rosenberg	Aerojet TechSystems Company
Robert Salkeld	Consultant
Donald R. Saxton	NASA Marshall Space Flight Center
James M. Shoji	Rockwell International
Michael C. Simon	General Dynamics
William R. Snow	Electromagnetic Launch Research, Inc.
Robert L. Staehle	Jet Propulsion Laboratory
Frank W. Stephenson, Jr.	NASA Headquarters
Wolfgang Steurer	Jet Propulsion Laboratory
Richard Tangum	University of Texas, San Antonio
Mead Treadwell	Yukon Pacific
Terry Triffet	University of Arizona
J. Peter Vajk	Consultant
Jesco von Puttkamer	NASA Headquarters
Scott Webster	Orbital Systems Company
Gordon R. Woodcock	Boeing Aerospace Company

The following people participated in the summer study as guest speakers and consultants:

Edwin E. "Buzz" Aldrin	Research & Engineering Consultants
Rudi Beichel	Aerojet TechSystems Company
David G. Brin	California Space Institute
Joseph A. Carroll	California Space Institute
Manuel I. Cruz	Jet Propulsion Laboratory
Andrew H. Cutler	California Space Institute
Christopher England	Engineering Research Group
Edward A. Gabris	NASA Headquarters
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