NASA in the 21st Century: A Vision of Greatness

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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 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.

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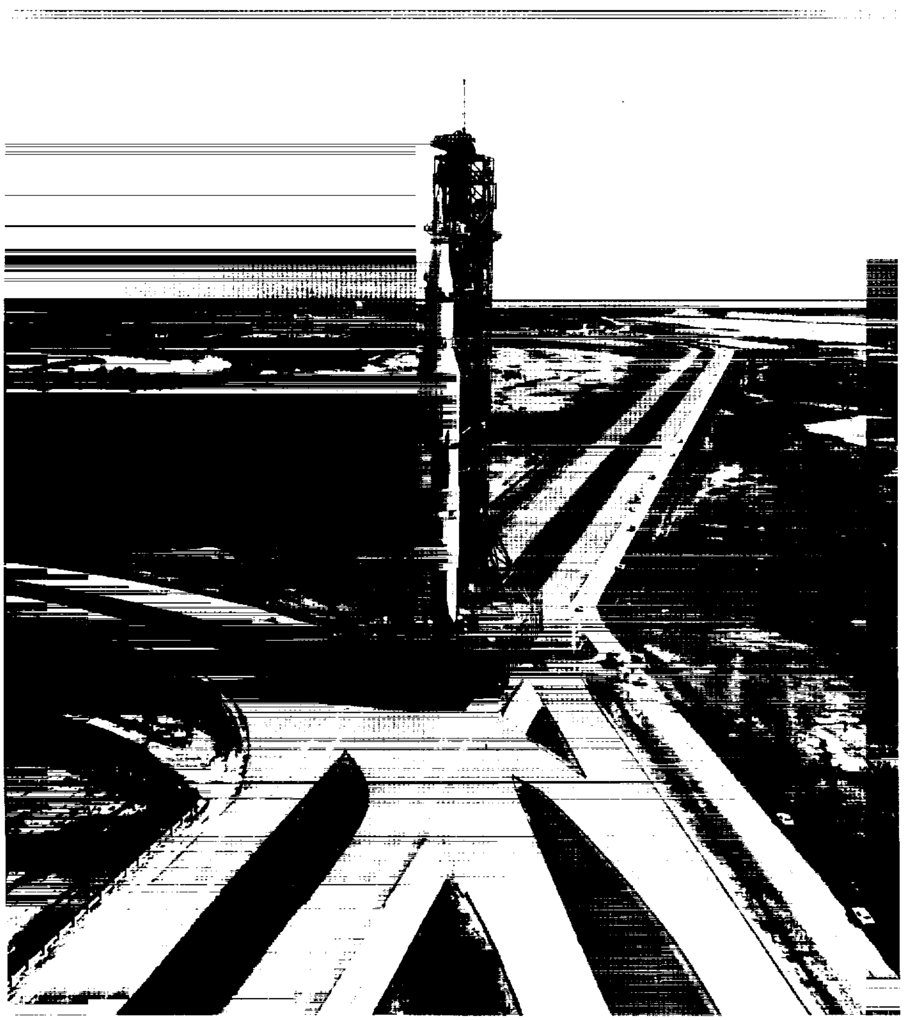
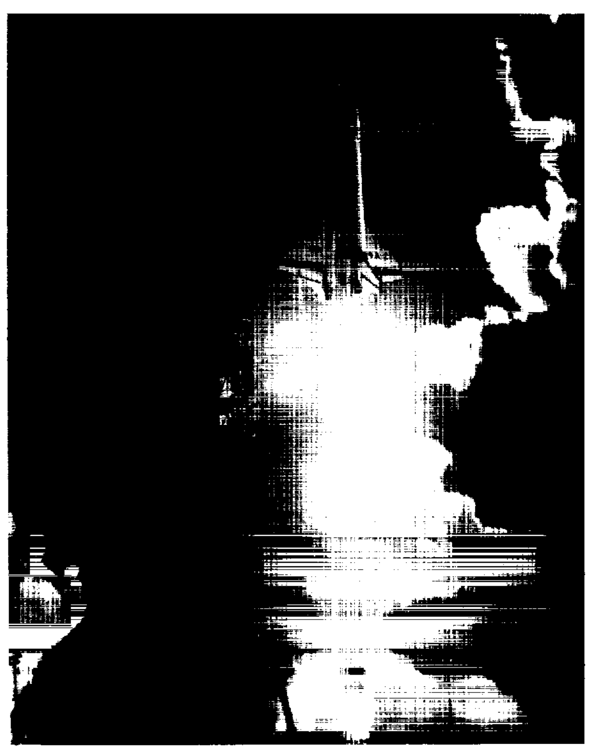


Apollo 14 Rollout, Nov. 9, 1970

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

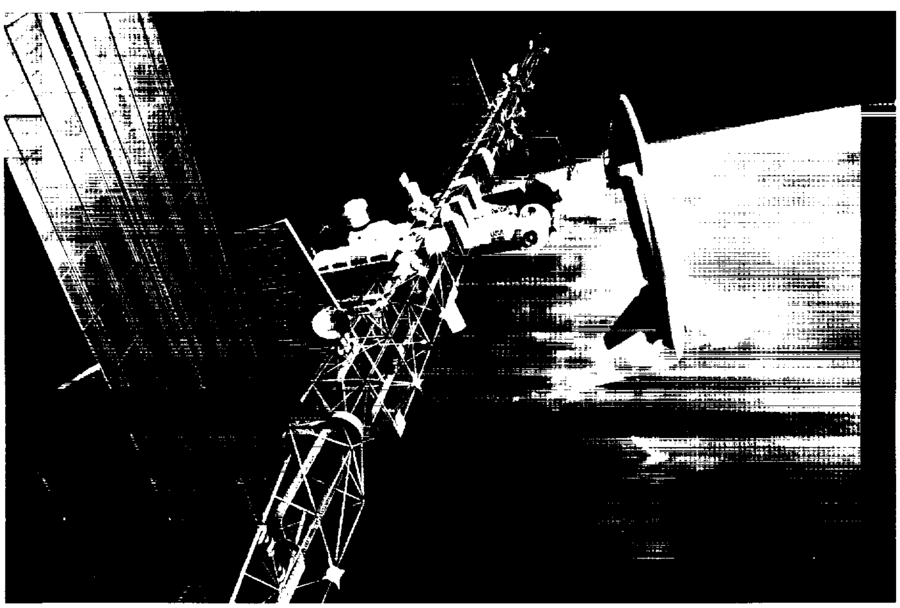
President Richard M. Nixon chose a very specific vision which, if successful, would have provided important commercial benefits to the United States and, if realized during his term of office, would have been a credit to his administration. He envisioned NASA as providing economical access to space for 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.

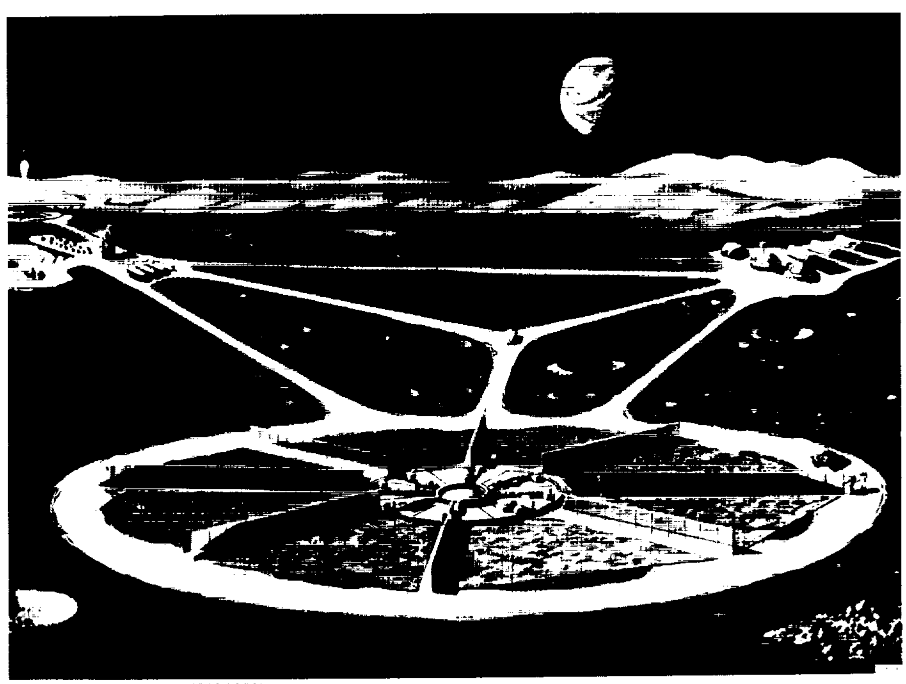
The directive to establish a permanently manned space station was a subsidiary mission in the Reagan era, subordinate to his vision of a Strategic Defense Initiative (SDI). However, to be worth $30 billion, the space station should really serve some worthwhile national purpose. Commercial applications 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.

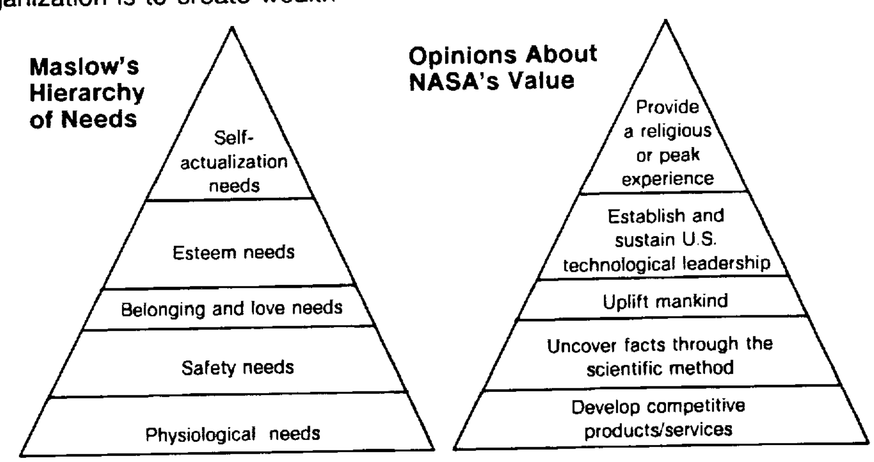


Figure 3

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 continosly 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.

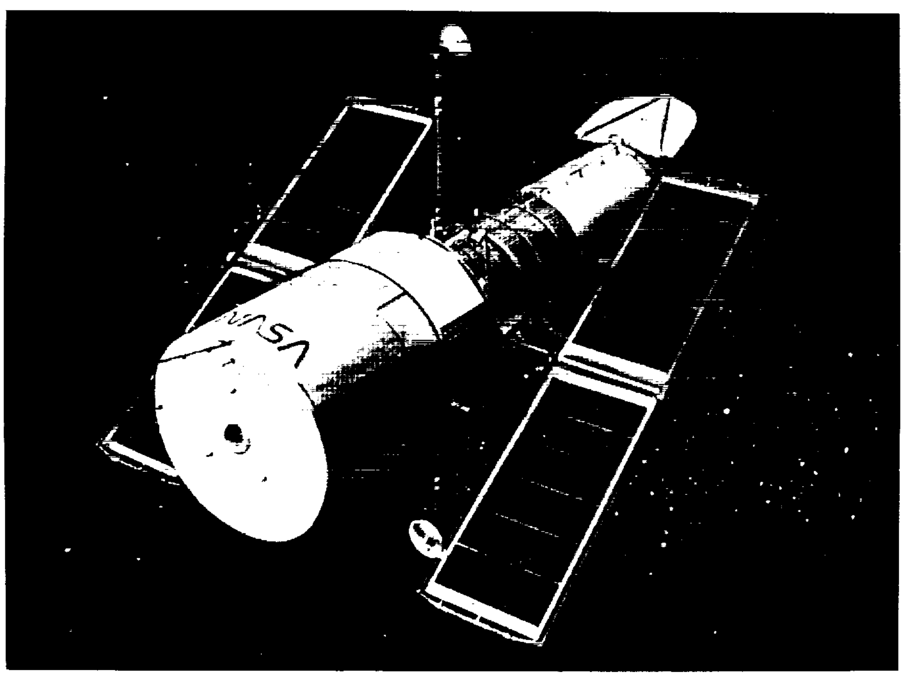


Figure 4

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

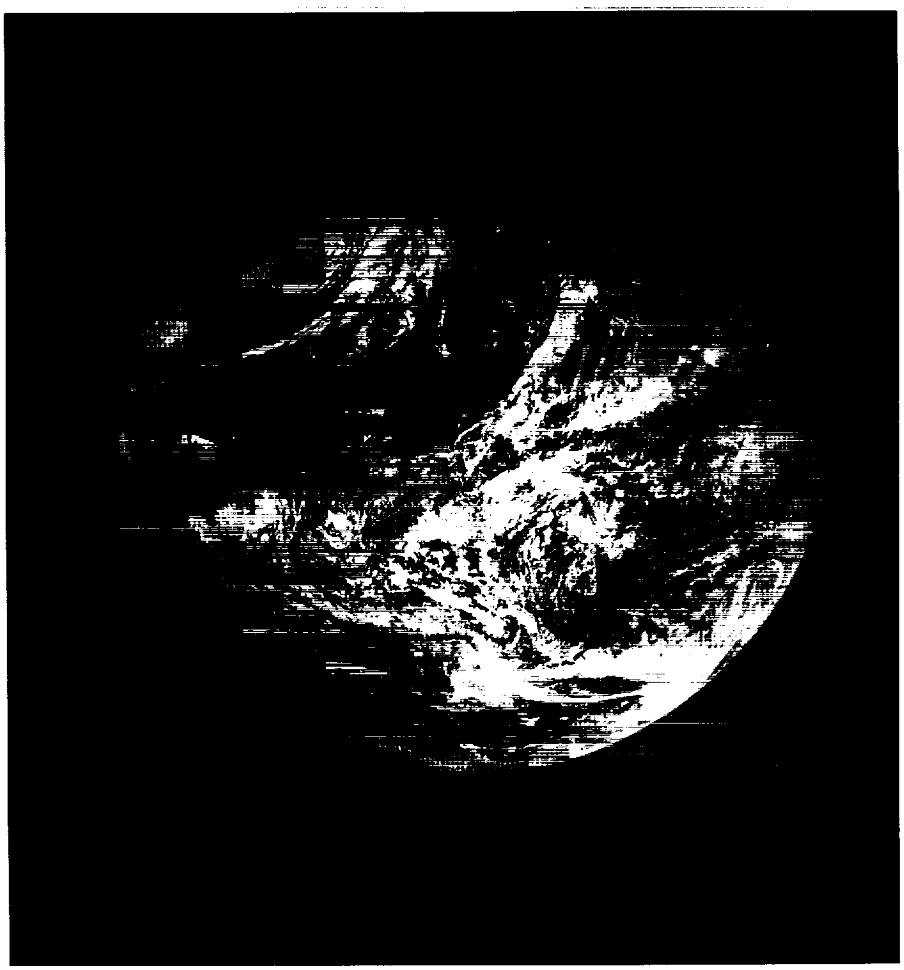
The "Planet Earth" consumer is literally consuming the planet:

> 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.

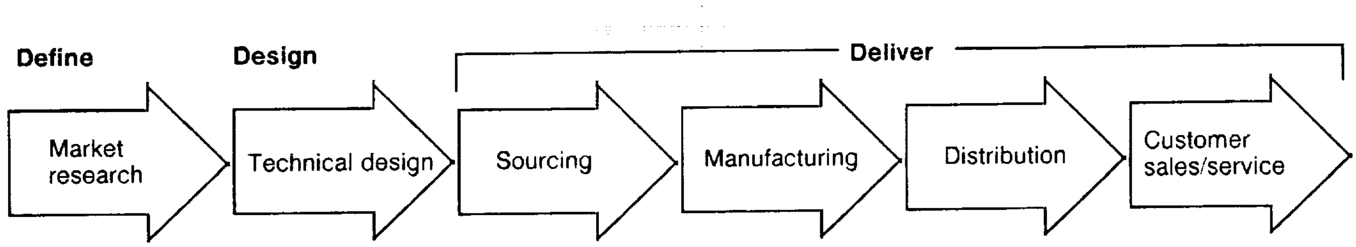
- Provide technology design initiatives that demonstrate regard for ecological limitations.

- 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.

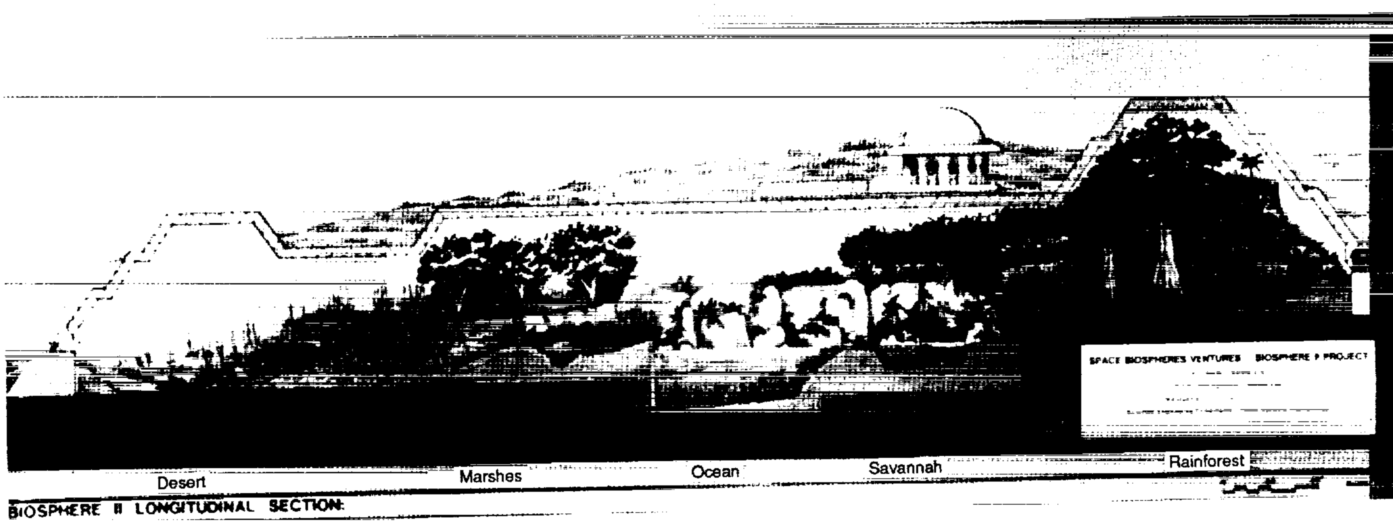


Figure 5

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 transpor-tation	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

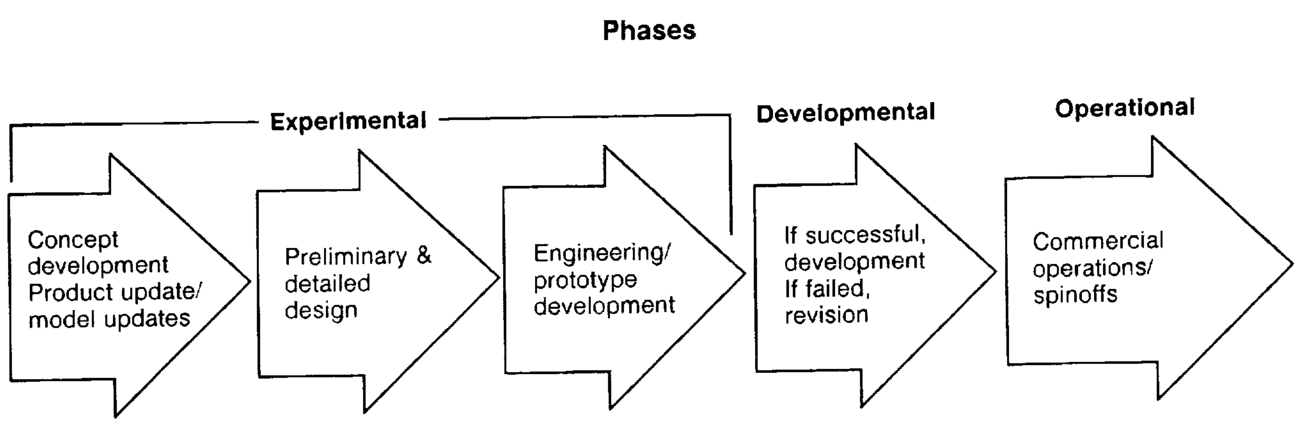
TABLE 4 *(concluded).*

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*

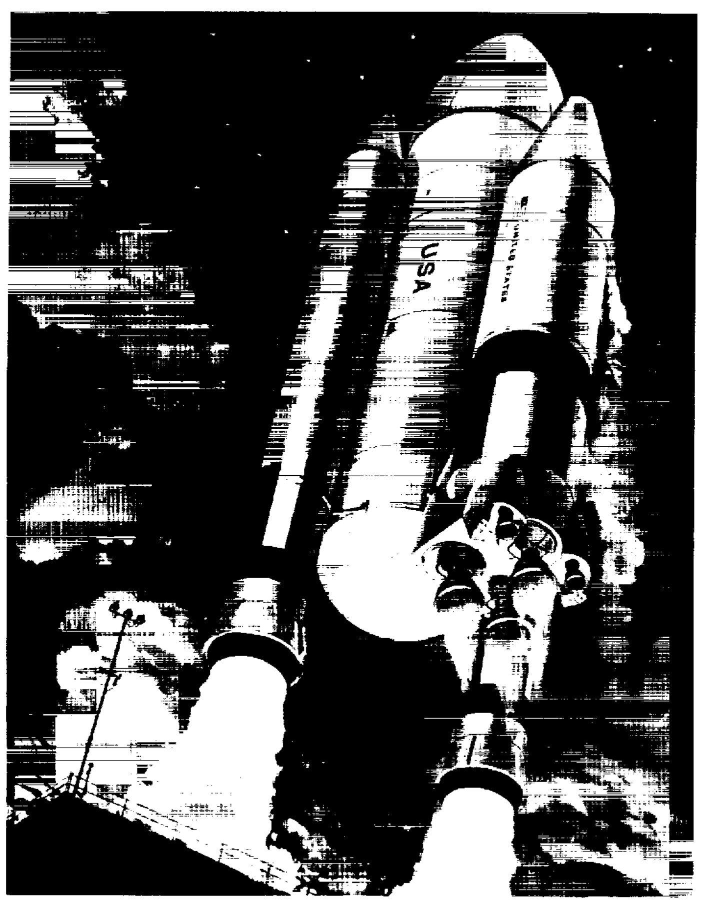
Country/agency	Focus	Philosophy	Strengths/weaknesses
U.S.A./NASA	Unmanned exploration Manned spacefaring	Massive technological leaps in R&D objectives	Bush commitment to take a fresh look Continually changing vision/funding
U.S.S.R.	Put man on Mars within next 25 years	Gradual development of space capabilities	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)

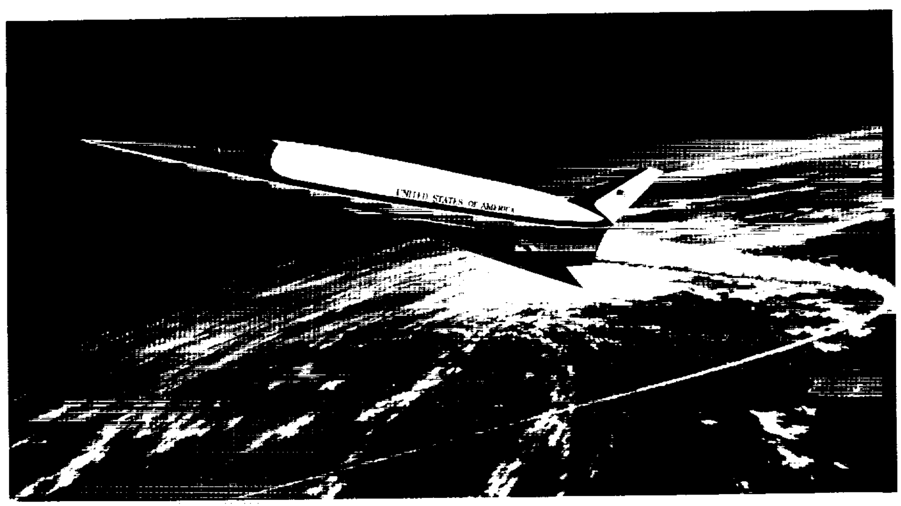
Technologies developed for the national aerospace plane (and spinoffs from that technology development) would greatly improve the competitive position of the United States in the aerospace field. This revolutionary class of vehicles would be able to take off and land horizontally on standard runways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

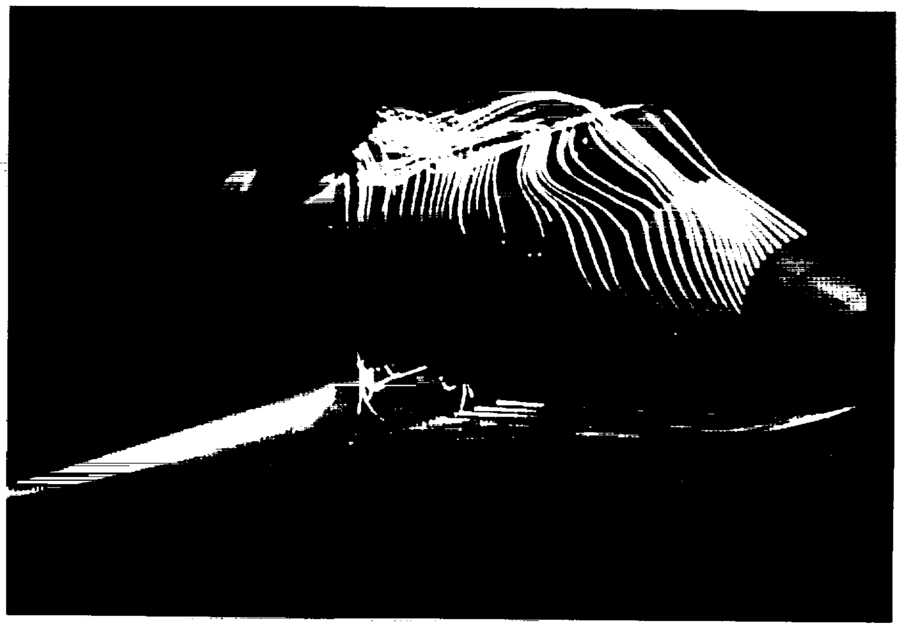
Its "scramjet" engines would burn a mixture of hydrogen and air, thus obviating the need to carry liquid oxygen. Its horizontal takeoff and landing (HOTOL) capability would eliminate the need for vertical launch facilities currently required for the Space Shuttle and unmanned boosters. These two capabilities 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.

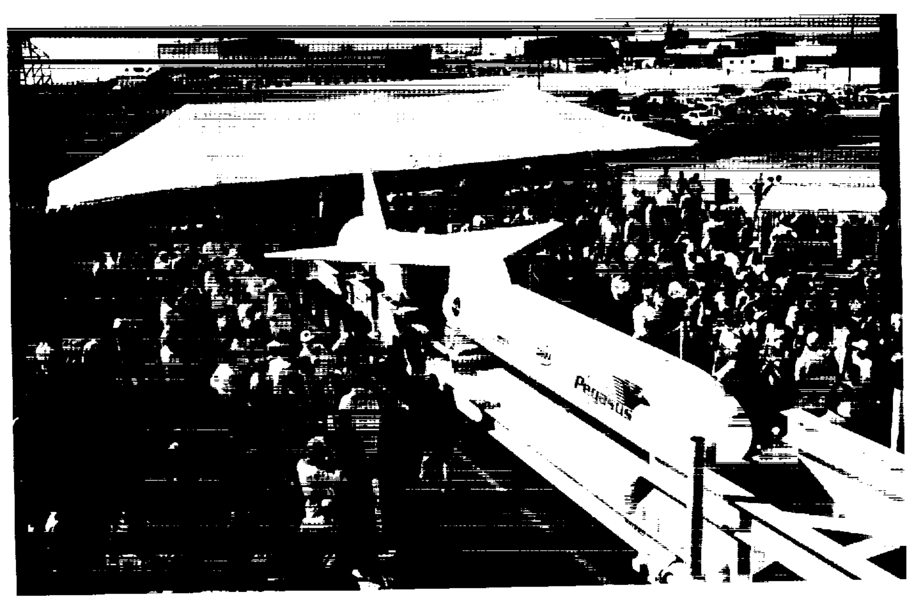


Figure 8

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.

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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).

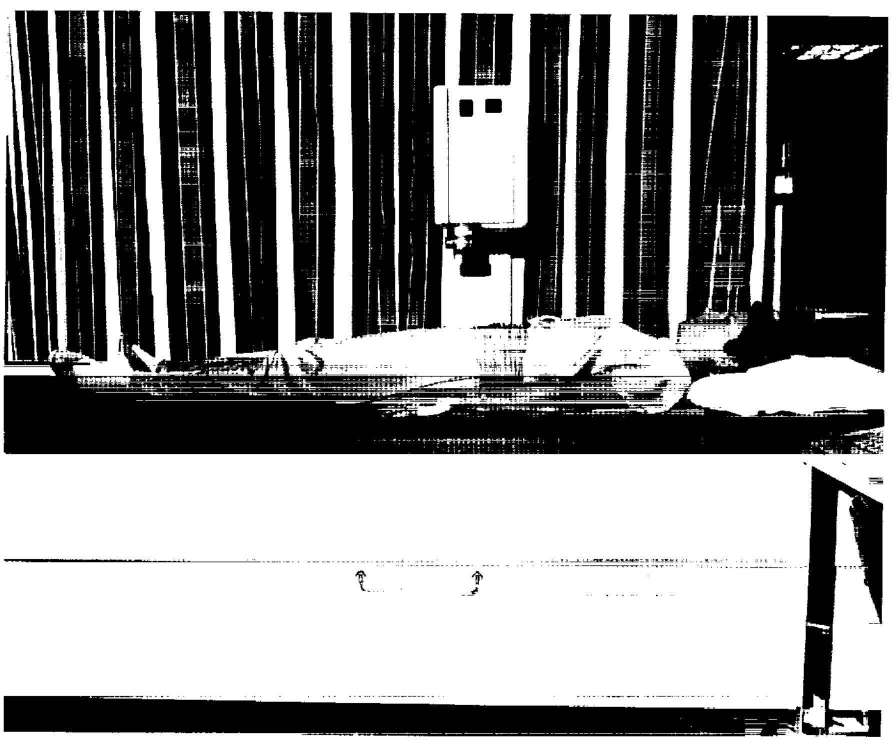
Lunar Greenhouse

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 bone 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.

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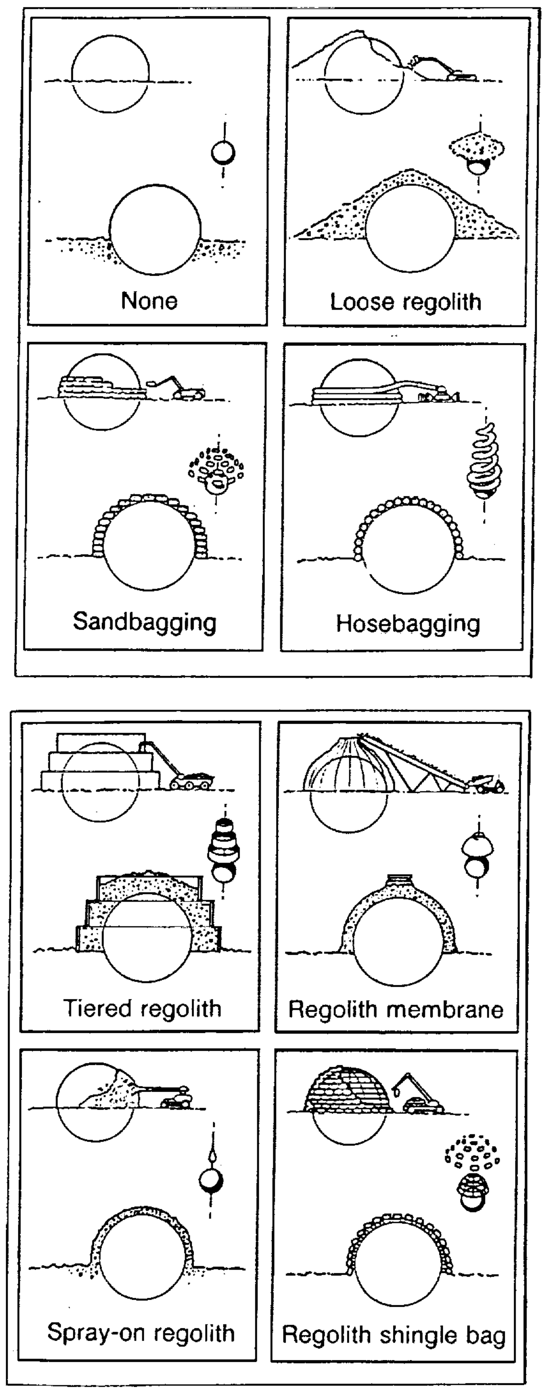
Space Station *Freedom* will have a life science research facility that will include a centrifuge system (1.8-2.5 meters in diameter) that produces an environment with gravity levels of 0.01-2.0 *g*. This is a first step in a program that requires acceleration devices in order to analyze the effects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

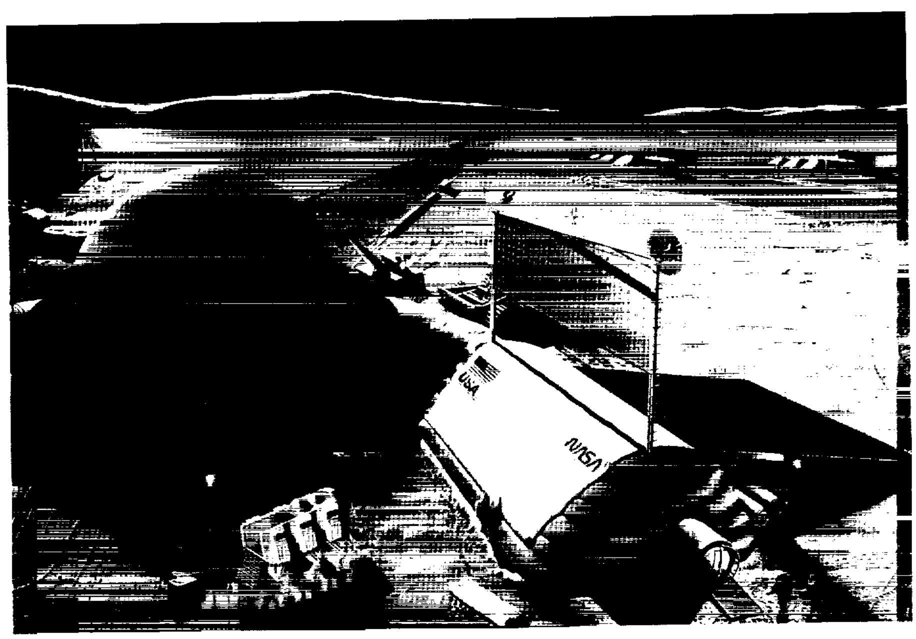


Options for Habitat Radiation Shielding

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

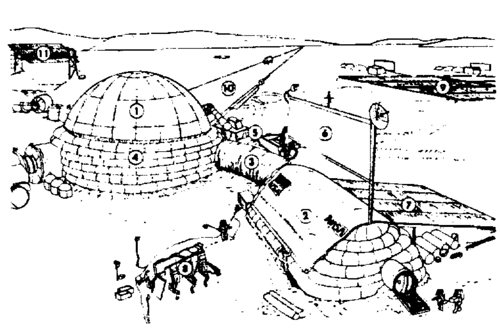
The U. S. Commerce Department projects that space venture



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



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

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).

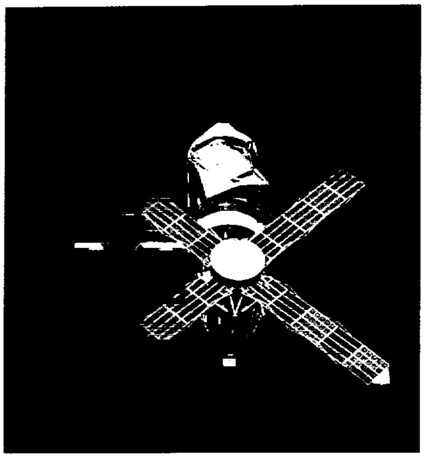
The United States is not alone in stimulating private participation: The Europeans and the Japanese are aggressively seeking opportunities to develop and provide products and processes to the global space industry.

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).

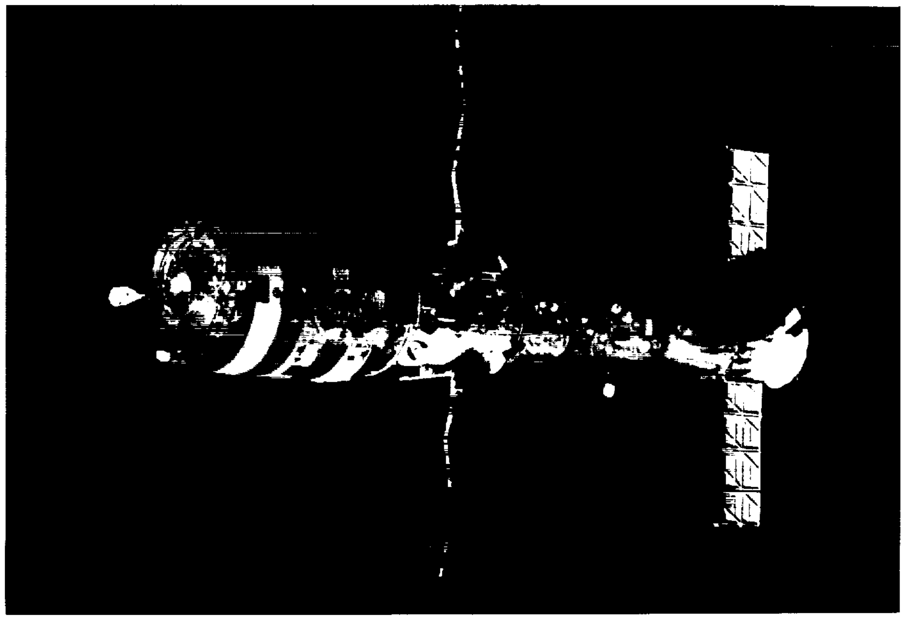
Nippon Electric Company, Mitsubishi Electric, and Toshiba, each a $15 billion plus company and a vertically integrated maker of microelectronics, computers, telecommunications equipment, and other high technology products, previously relied on government contracts and U.S. technology to expand their 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



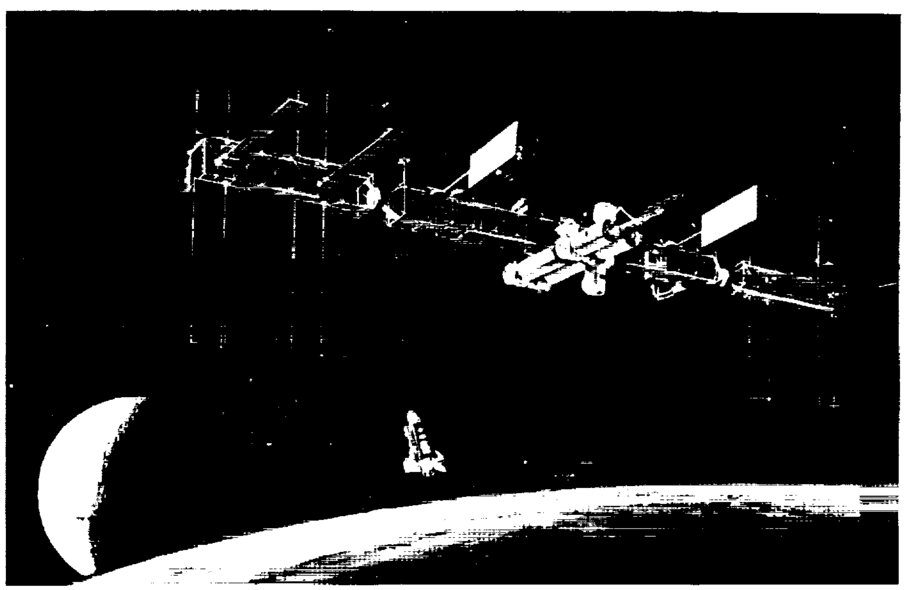
Skylab, launched May 14, 1973; occupied three times during 1973 and 1974; fell back into the atmosphere July 11, 1979



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.

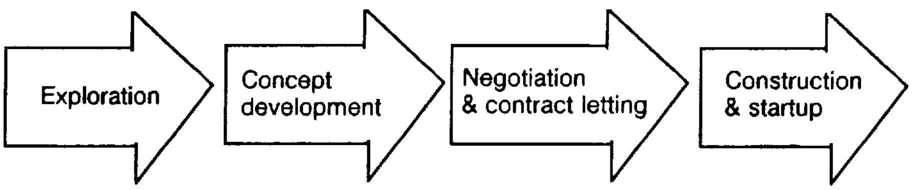
Once exploration of potential sites is completed, a destination is selected, and colonization has been decided on, the major resource development project begins to evolve (see table 12), following a very clear and well-tested path from concept development, through negotiation and contract letting, to 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*



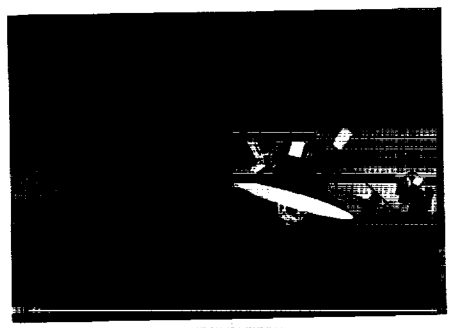
Development of a particular destination in space is not free from the need to innovate and advance. We have no experience in establishing large communities that are completely dependent on their infrastructure for oxygen. We have not yet developed construction techniques for connecting materials that 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.



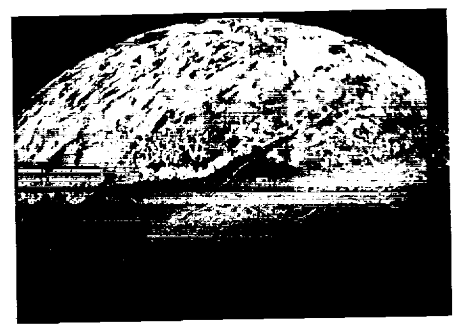


Figure 9

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.

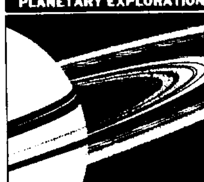
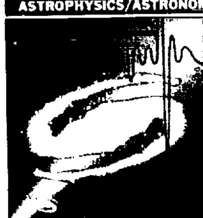
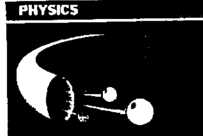
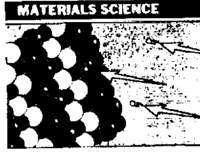
This view of Triton is a mosaic of a number of close-up photographs taken on August 25, 1989, during the closest encounter of Voyager 2 with the satellite of Neptune. Triton has a complex surface, with a few craters, probably made by comets. Triton probably has a silicate core about 1250 miles in diameter 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.

Figure 10

Mars Rover Sample Return

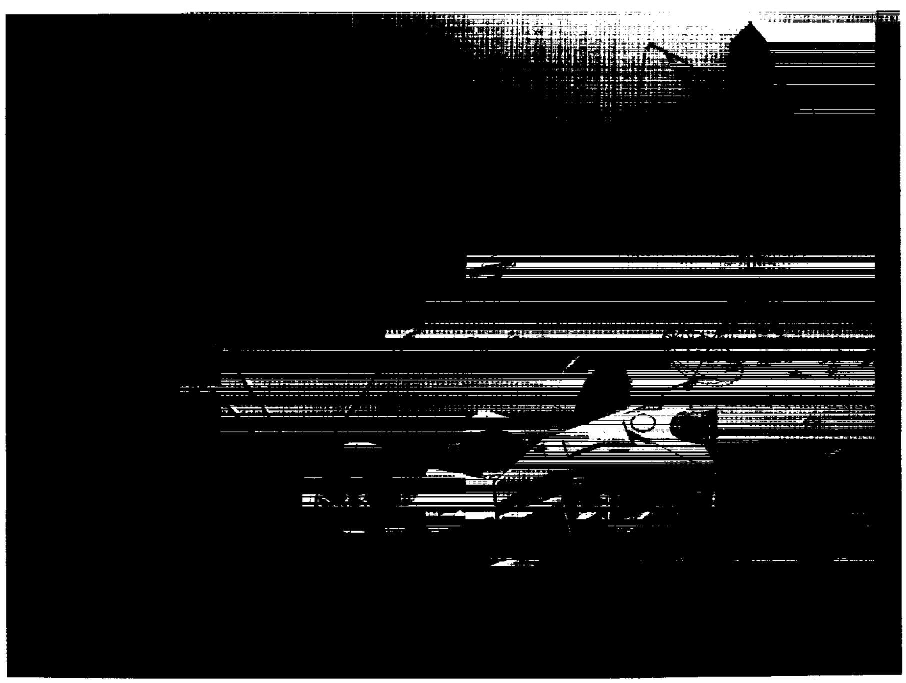
Robotic collection and return to Earth of martian geologic samples would greatly increase our understanding of the history of Mars and would help us make workable plans for human exploration of Mars. Analysis of the samples would help establish how recently volcanoes have been active, what might have 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

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.



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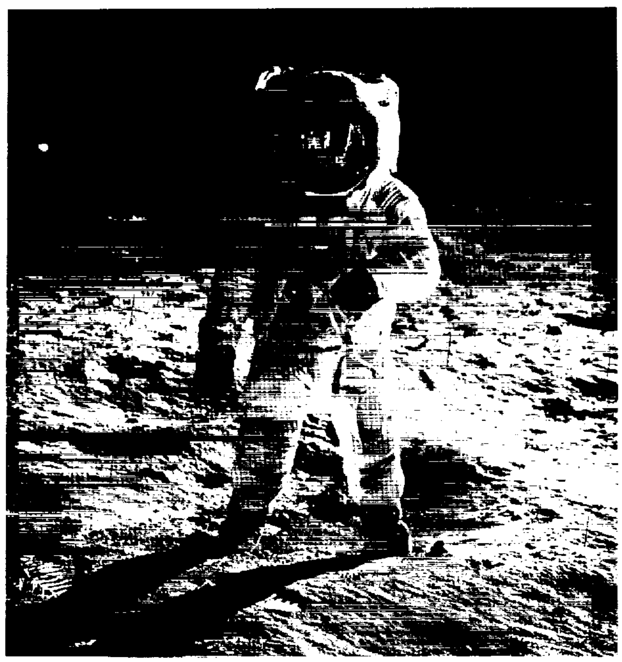
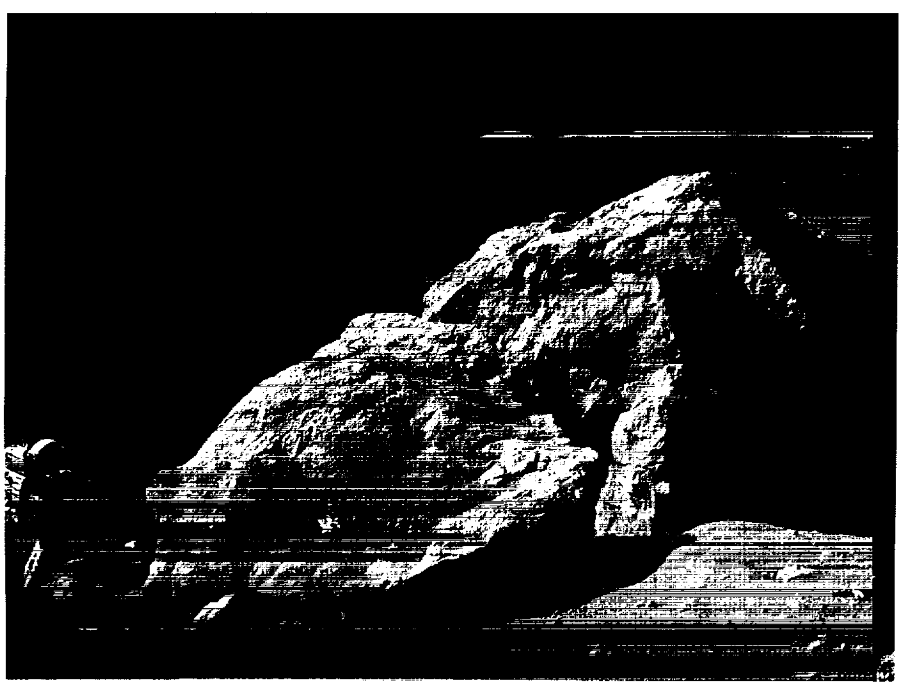




Men on the Moon – the First and Last (So Far)

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

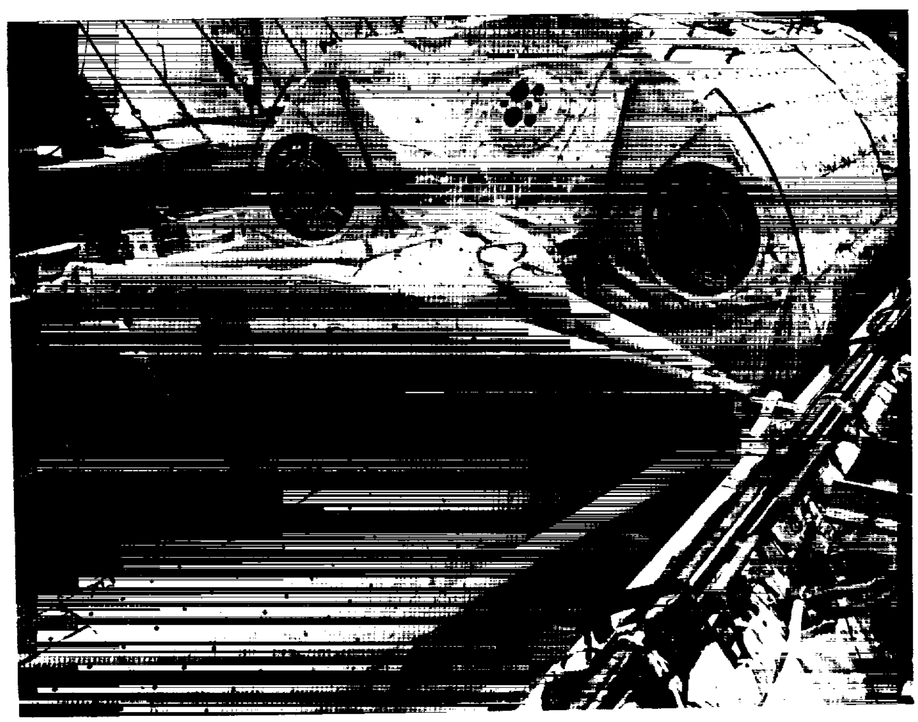
The advantage of governmental development and management of supporting infrastructure is that it provides access to life-sustaining facilities to small as well as large enterprises and to individuals of all economic levels, enabling them to undertake entrepreneurial as well as corporate economic activities.

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

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

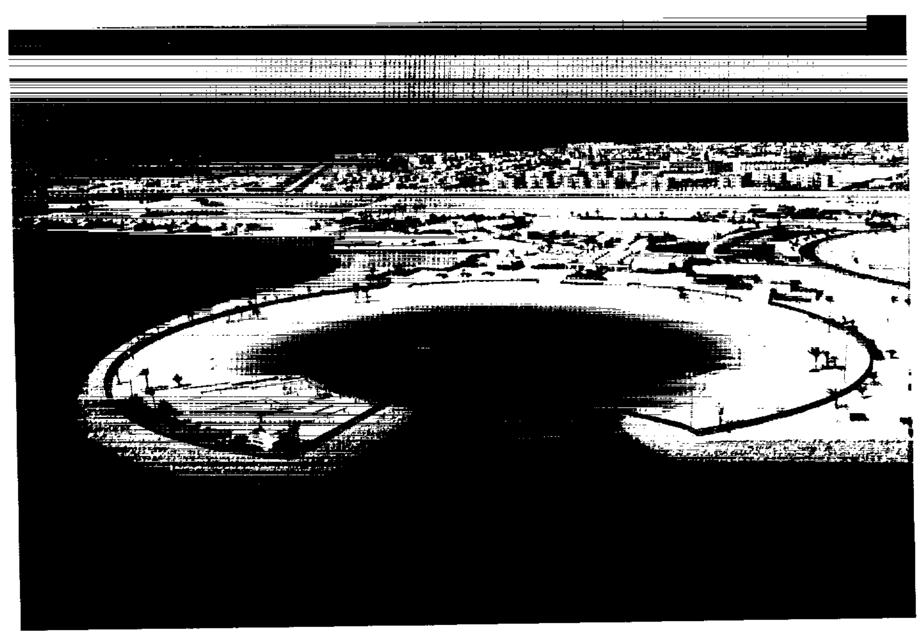


Figure 13

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.

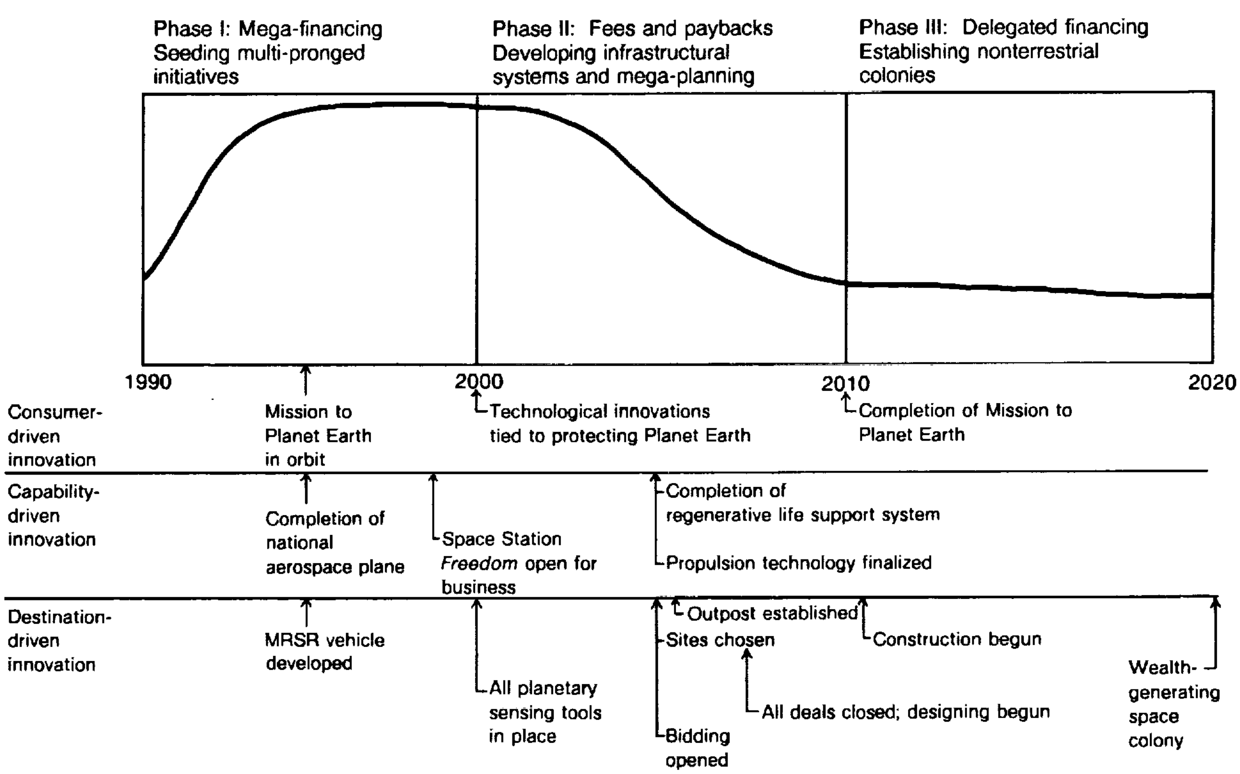
Once the infrastructure technologies and exploration investigations reach closure, mega-planning can begin for colonization of the Moon and

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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