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Issues for Further Study

Hubert Davis

Overview

The mind-expanding nature of our future activities beyond Earth leads to a plentiful flow of new ideas and major improvements on earlier concepts. The recent discovery of numerous Earth-crossing asteroids, for example, adds greatly to the magnitude and diversity of the material resources in space of which we are aware. However, a serious question arises. Does there exist any orderly process for gaining general awareness of these new ideas or for evaluating their importance to society? Membership in a specific academic, government, or industrial group, coupled with persistence and eloquence, are today's means of hearing and being heard. These mechanisms may not, however, be the optimal means for flushing out and eventually implementing the best new ideas.

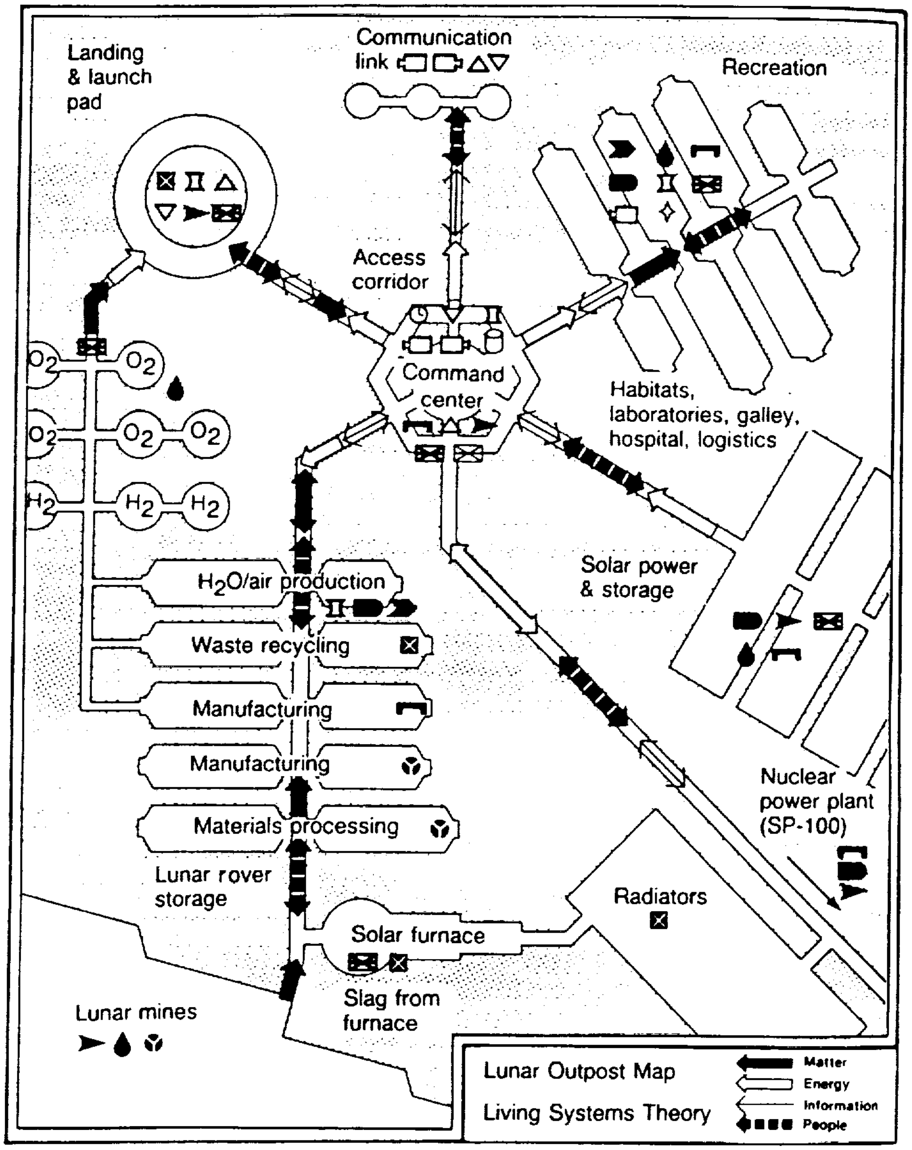
One small step toward achieving the goal of preserving for use the best of the suggested new concepts is the "systems study" approach. In this approach, a set of future needs and a straightforward means of satisfying these needs are described in quantitative terms as a "scenario." This scenario is then set forth as a benchmark case for testing the relative merit of new, alternative means of meeting one or more of these needs. This systems approach should be used to assess the merits of new concepts and to identify the most important advancements in technology needed to establish or enhance the merit of the concept. (The map of a lunar outpost illustrates the application of another kind of systematic study, known as "general living systems" theory and analysis.)

Ideally, as needs change and new concepts and data become available, the "baseline" scenario should be revised to incorporate some of the new ideas. When that occurs, the technology development of the newly incorporated approaches should actively begin to remove residual uncertainties. But the effort should, in most cases, stop short of "prototyping."

It is very important to remain as generic or flexible as practical in order to be ready to adapt the scenarios and associated technologies to changes in the social norms, political climate, and economic health of the nation.

To further complicate matters, once a new "baseline" scenario is accepted for testing of new concepts, earlier conclusions must also be reexamined since former "new" ideas that were earlier rejected may be found to be highly desirable given the new scenario.

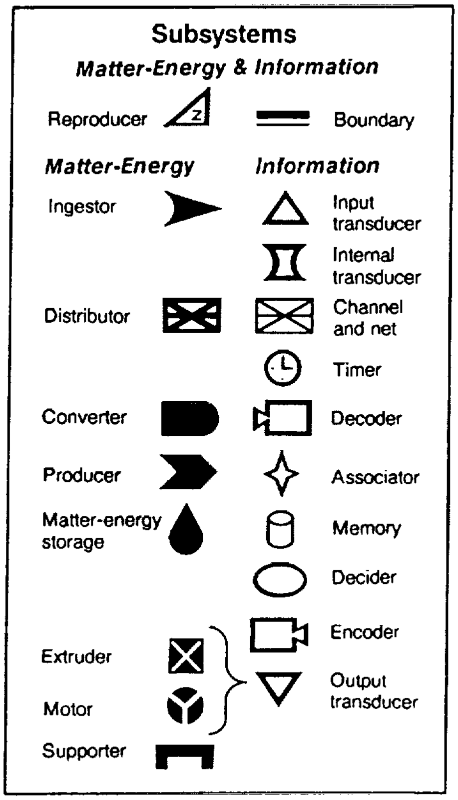
Some formalized means should be found for establishing, testing and refining, utilizing and maintaining


Landing & launch pad
Communication link
Recreation
Access corridor
Command center
Habitats, laboratories, galley, hospital, logistics
Solar power & storage
Nuclear power plant (SP-100)
Radiators
O_2
H_2
H_2O/air production
Waste recycling
Manufacturing
Manufacturing
Materials processing
Lunar rover storage
Solar furnace
Slag from furnace
Lunar mines
Lunar Outpost Map
Living Systems Theory
Matter
Energy
Information
People

Lunar Outpost Map

General living systems theory is a conceptual integration of biological and social approaches to the study of living systems. Living systems are open systems that input, process, and output matter and energy, as well as information which guides and controls all their parts. In human organizations, in addition to matter and energy flows, there are flows of personnel, which involve both matter and energy but also include information stored in each person's memory. There are two types of information flows in organizations: human and machine communications and money or money equivalents. Twenty subsystem processes dealing with these flows are essential for survival of systems at all levels.

The general procedure for analyzing such systems is to map them in two- or three-dimensional space. This map of a lunar outpost indicates its subsystems and the major flows within it. Such an analysis would take into account the primary needs of human systems—foraging for food and other necessary forms of matter and energy; feeding; fighting against environmental threats and stresses; fleeing from environmental dangers; and, in organizations which provide a comfortable, long-term habitat, perhaps reproducing the species. This study would analyze the effects on human social and individual behavior of such factors as weightlessness or 1/6 gravity; limited oxygen and water supplies; extreme temperatures; available light, heat, and power; varying patterns of light and dark; and so forth. A data bank or handbook could be developed of the values of multiple variables in each of the 20 subsystems of such a social system.



a baseline scenario of long-range space activities and of supporting, refereeing, and reviewing the application of this scenario in system studies of new concepts. This process was begun by NASA's Office of Aeronautics and Space Technology (OAST) in the mid-1970s, but it was abandoned in the late 1970s because of budgetary constraints and the press of nearer term needs, as perceived by NASA management. Total cost to NASA of restoring and enhancing these efforts would be only 0.01-0.02 percent of NASA's yearly budget.*

Lunar Resource Utilization

Resource Prospecting

Early priority should be given to an automated lunar polar spacecraft to perform a global survey of the Moon with instruments appropriate to detect the presence, location, and concentration of useful materials. This mission may have to be repeated or extended to follow up on areas of particular scientific and economic interest.

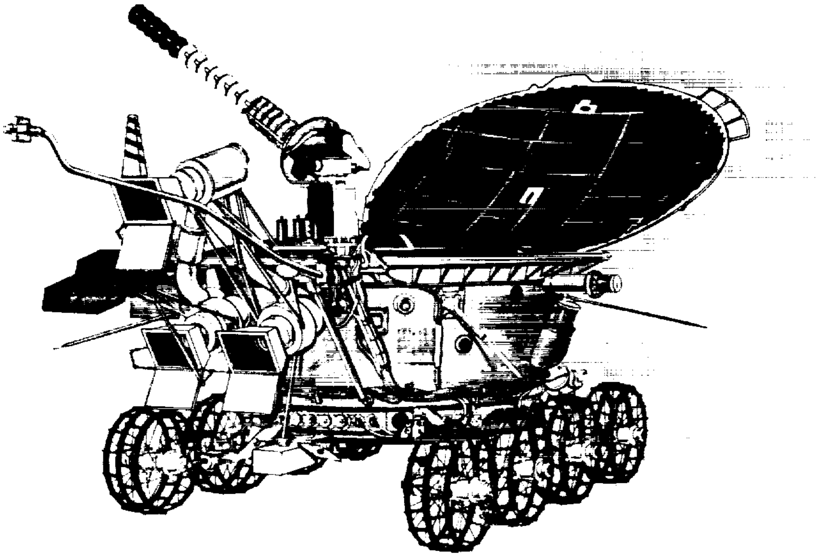
Lunar Assay

Automated surface rovers, with the capabilities of coring, assaying materials, and possibly returning samples to Earth, should be sent out to gather data. This activity should be completed several years before final commitment is made to the location of the initial lunar base. (See figure 26.)

Figure 26

Lunokhod 1 and Apollo 17 Rover

a. Automated vehicles roving over another planetary body were first used in the early 1970s by the Soviets on their Lunokhod missions. These lunokhods were capable of traveling tens of kilometers at speeds up to 2 km/hr. They were run from a Soviet control center by a crew of five—commander, driver, navigator, operator, and onboard-systems engineer. The crew used television images and systems readouts to drive and operate the vehicles. The lunokhods carried several scientific instruments, including an x-ray fluorescence spectrometer for determining the chemical composition of lunar regolith. Lunokhod 1 traveled about 10 km and Lunokhod 2 traveled 37 km, each over a period of months.



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* Since this report was drafted, significant long-term planning activities have been undertaken, initiated by the work of the National Commission on Space. The commission's report, *Pioneering the Space Frontier*, is available from Bantam Press.

Lunar Mining

Mining the Moon will present new challenges. Surface mining will probably be the norm, although subsurface mining may be necessary in some cases. The movement of large amounts of material will degrade the scientific utility of the mining site, alter its appearance, and release gases into the tenuous lunar atmosphere. Thus, the effect of lunar mining on the environment will have to be carefully evaluated before mining begins.

Process Development

Ideas for getting oxygen from lunar materials have been generated since the 1960s and '70s.* Now, preliminary design studies and process engineering should

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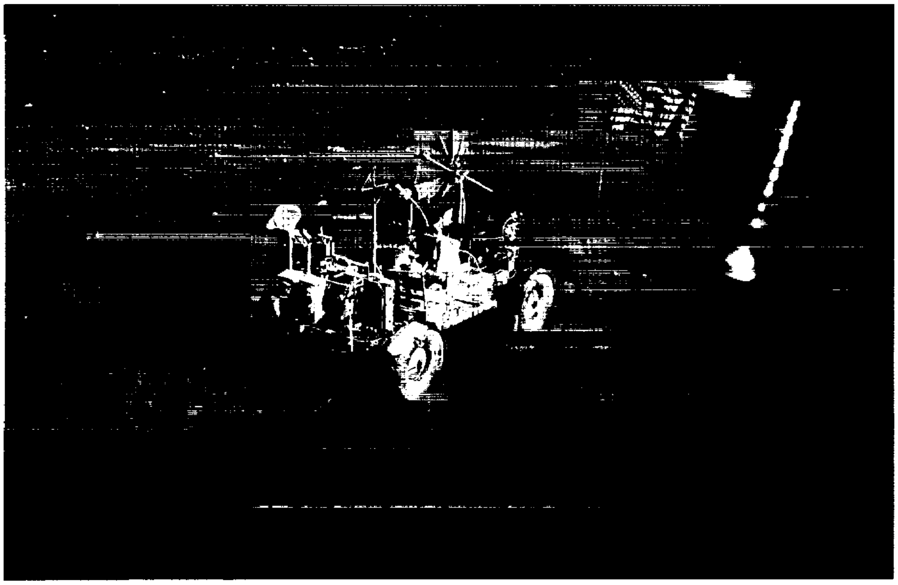
* See, for example,

Rosenberg, S. D.; G. A. Guter; and F. E. Miller. 1964. The On-Site Manufacture of Propellant Oxygen Utilizing Lunar Resources. Chem. Eng. Prog. **62**:228-234.

Rosenberg, S. D.; G. A. Guter; and F. E. Miller. 1965. Manufacture of Oxygen from Lunar Materials. Ann. N.Y. Acad. Sci. **123**:1106-1122.

McKay, David S., and Richard J. Williams. 1979. A Geologic Assessment of Potential Lunar Ores. In Space Resources and Space Settlements, NASA SP-428, pp. 243-255.

Rao, D. Bhogeswara; U. V. Choudary; T. E. Erstfeld; R. J. Williams; and Y. A. Chang. 1979. Extraction Processes for the Production of Aluminum, Titanium, Iron, Magnesium, and Oxygen from Nonterrestrial Sources. In Space Resources and Space Settlements, NASA SP-428, pp. 257-274 .



b. The Rover was used on Apollo missions 15, 16, and 17. Here, the Apollo 17 Rover is seen near the Lunar Module. While not intended for automated operations, the basic rover systems (motors, power, communication, TV, steering and control) could easily be adapted to unmanned exploration traverses. Experience gained in the design and operation of the Apollo Rover, combined with the Soviet Lunokhod experience, will provide a basis for future lunar and martian rover designs.

be performed to derive a comprehensive plan involving laboratory experimentation, bench testing, and pilot plant development for the purpose of testing, developing, and refining the beneficiation and feedstock conversion steps necessary to produce useful products from lunar regolith material. (See figure 27.) This plan should permit examination and quantification of the optimal conversion pressure, temperature, and concentration, conversion efficiency, energy requirements, heat rejection, catalysts, carrier fluid consumption, and the scale effects so as to allow confident design of an operational chemical plant.

Ancillary Equipment Development

Equipment for automated mobility; solid material conveyance; feedstock material insertion and extraction (into and from the converter); water vapor condensation; electrolysis; gaseous oxygen and hydrogen refinement, movement, and storage; oxygen liquefaction; liquid oxygen storage and transport; and other purposes must be conceptualized, designed, tested, and developed for the minimum

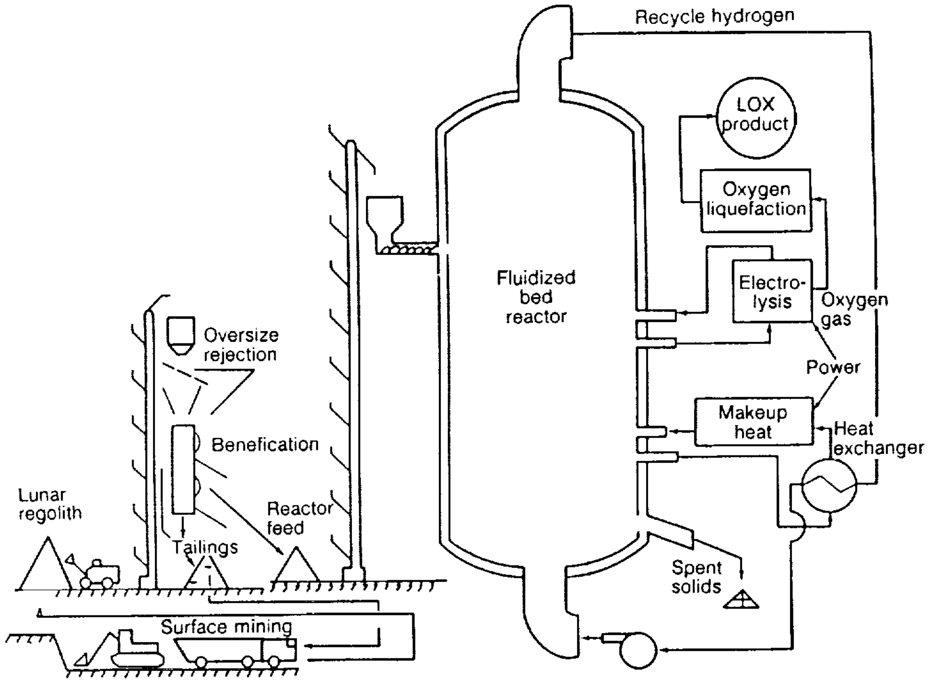


Figure 27

Oxygen From Lunar Ilmenite

In this concept for a lunar oxygen plant, ilmenite ($FeTiO_3$) is concentrated from lunar regolith and then fed into a three-stage fluidized bed. In the upper stage, the ilmenite concentrate is preheated by hot hydrogen passing through the powdered ilmenite. The hot ilmenite then goes into the second stage, which is the main reactor bed. Here, even hotter hydrogen reacts with the ilmenite, extracting one oxygen atom from each ilmenite molecule, forming H_2O, metallic iron (Fe), and TiO_2. The H_2O and excess hydrogen are extracted and circulated through an electrolyzer, which breaks down the H_2O. The released oxygen is then cooled, compressed, and stored as liquefied oxygen. The spent feedstock enters the third stage, where heat is extracted by hydrogen gas before the spent material is dumped from the reactor.

of human intervention. (See figure 28.)

A virtue of these activities is that each of these elements is individually a rather straightforward application of advanced automatic or teleoperative technology. And with the appropriate mix of this technology and the human element, the optimal manufacturing capacity can be placed on the Moon.

Development of Space Transportation Equipment

Large, automated orbital transfer vehicles and lunar landing vehicles must be better defined before we can quantify performance, life, and cost factors. Numerous technology developments will be needed before we can confidently begin full-scale development. The key technologies of these vehicles appear to be the following.

High performance oxygen/ hydrogen rocket engine: A new-generation rocket engine will be needed early. It should generate higher specific impulse than current engines (480-490 sec, as compared to 446 sec for the RL-10), produce a thrust of approximately 7500 lbf, provide moderate throttling capability, and be designed for long life with maintenance in space.

Figure 28

Ancillary Equipment at a Lunar Base

This lunar base sketch illustrates some of the ancillary systems that are necessary for a productive lunar base. The sketch includes a mining system, a processing plant, a construction-block-making unit, a solar power generator, a buried habitat and agricultural unit with solar lighting reflector, automated materials handling equipment, cryogenic storage tanks, surface transportation vehicles, communication antennas, and a rocket system for transportation to lunar orbit. All of these systems require technology development.

Owing to these requirements, an advanced space engine will have to be designed for a very high chamber pressure (1500-2000 psia) and a high expansion ratio (2000:1). (See figure 29.)

Cryogenic propellant handling and preservation: The ability to store, transfer, measure, and condition cryogenic fluids (including liquid oxygen, hydrogen, and argon) with zero loss requires extensive development and testing. (See figure 30.)

Aerobraking technology: Although theoretically very attractive for returning payloads to LEO, many uncertainties, including aerobraking equipment mass, must be resolved before aerobraking is practiced. (See figure 31.) Advanced concepts in guidance, navigation, and control will need investigation, particularly for uses that involve higher velocity return to Earth orbit. Early Shuttle-launched test missions should be considered.

Advanced composite structures: Overall spacecraft systems design using advanced composite structures requires data on micrometeoroid impact effects, cryogenic fluid compatibility, equipment attachment, inspection and repair, and other aspects.

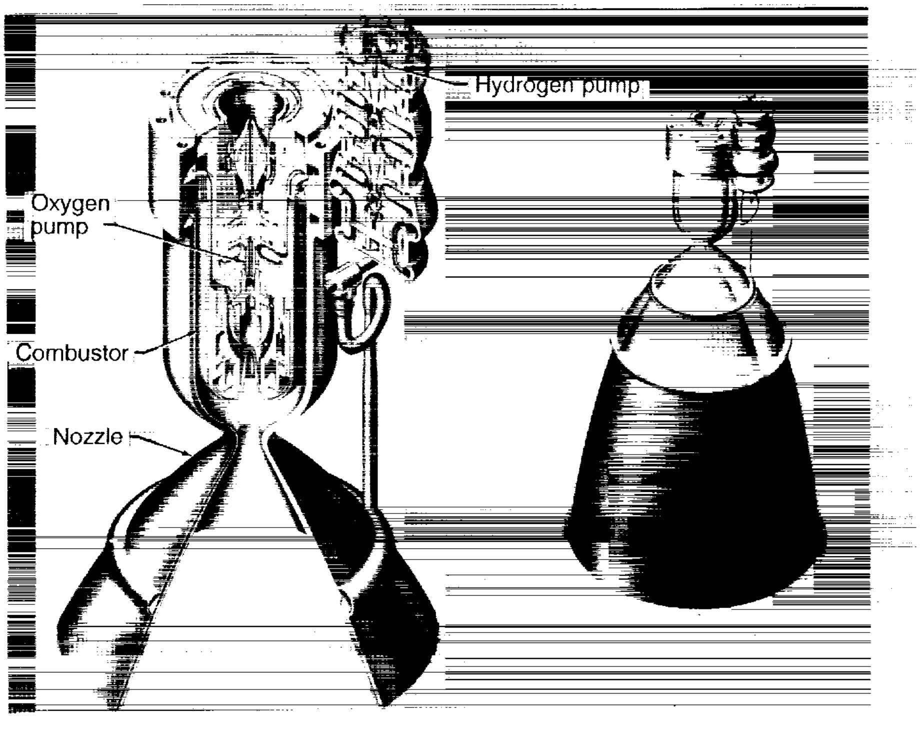


Figure 29

Advanced Engine

New, high performance engines for orbital transfer vehicles must be developed. Here is an oxygen-hydrogen engine concept developed by Aerojet TechSystems Company specifically for use in a reusable orbital transfer vehicle designed to shuttle between low Earth orbit and either geosynchronous Earth orbit or lunar orbit.

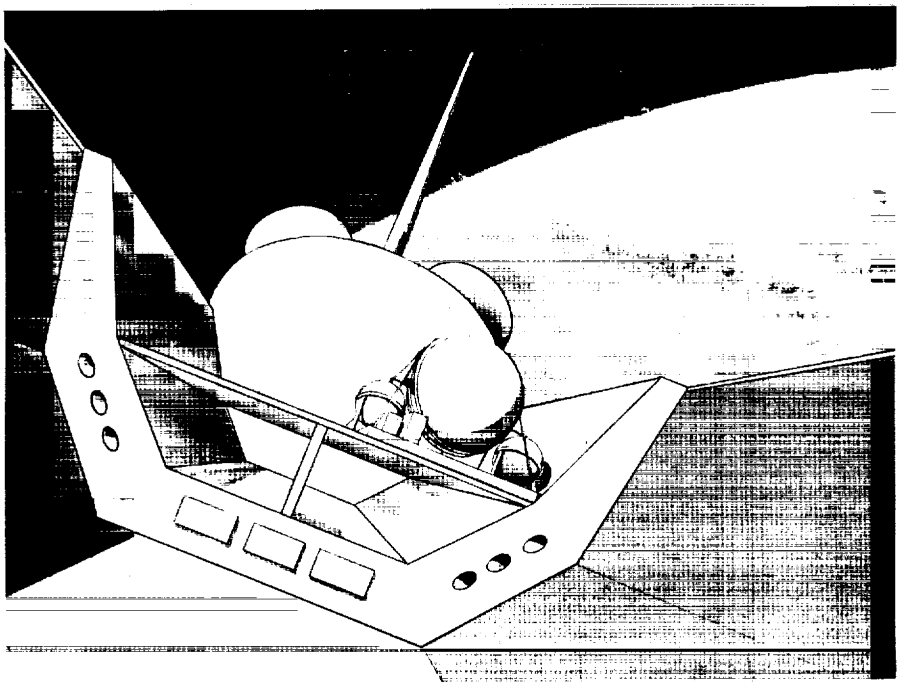


Figure 30

Cryogenics

Technology must be developed and tested for complex space operations. Here is a sketch of a proposed cryogenic fluid management experiment, which will test on the Shuttle orbiter some of the necessary equipment to transport, transfer, measure, and store cryogenic fluids in space. This technology is needed to make reusable orbital transfer vehicles and lunar landers practical. Cryogenic handling technology is also critical to future space operations that make use of lunar-provided rocket propellant.

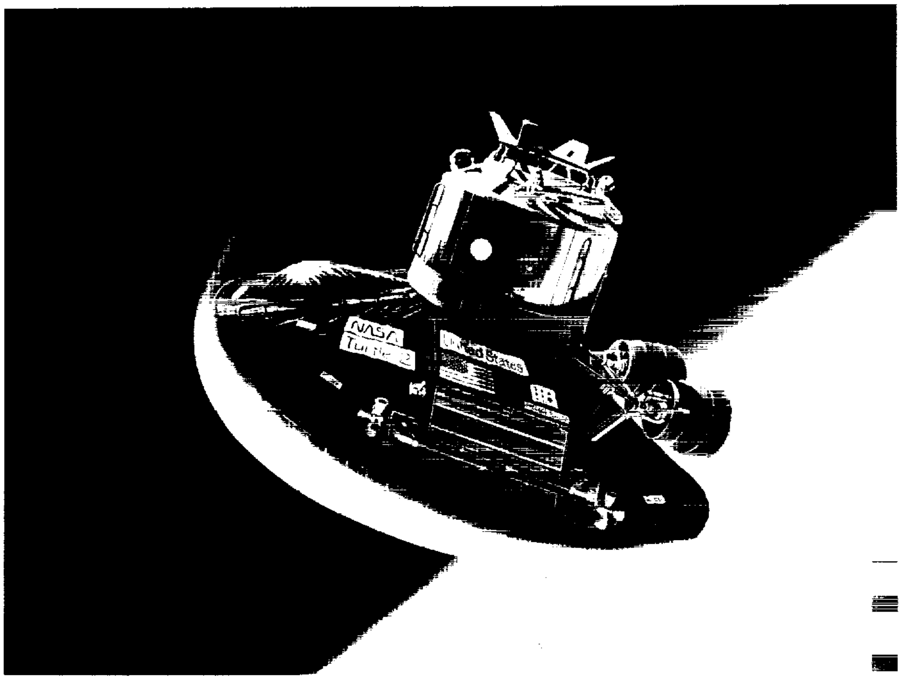


Figure 31

Aerobraking Technology

Aerobraking technology must be developed before efficient transfer can be made from lunar or geosynchronous orbit to low Earth orbit. Aerobraking is also necessary for any Mars return mission, whether manned or unmanned. Without aerobraking, considerable rocket propellant must be used to slow down a spacecraft coming toward the Earth. Here is an aerobrake on an orbital transfer vehicle returning from lunar orbit. The aerobrake uses friction with the Earth's uppermost atmosphere to slow down the vehicle and divert it to a low Earth orbit. This procedure requires a combination of very heat resistant brake surfaces, precisely known aerodynamic properties, and very careful trajectory and attitude control.

Artist: Pat Rawlings

Operations technology: The infant art and science of maintaining, servicing, storing, and checking out complex space vehicles (both manned and automated) whose entire service life is spent in the space environment requires nurturing. (See figure 32.) Many facets of this problem require both hardware and software development. A design goal of operations technology must be efficiency. Current operation procedures for the Space Shuttle are so costly that, if applied directly to reusable orbital transfer vehicles, they could invalidate the cost-savings potential of these vehicles over expendable vehicles.

Debris control, collection, and recycling: Our future operations in space must not litter. Active measures are needed to prevent littering. A plan of action is needed to remove discarded objects from valuable space "real estate." (See figure 33.) And the technology for recycling waste materials in space needs to be developed. The Shuttle external tank represents a resource in space which can be employed—perhaps early in the space station

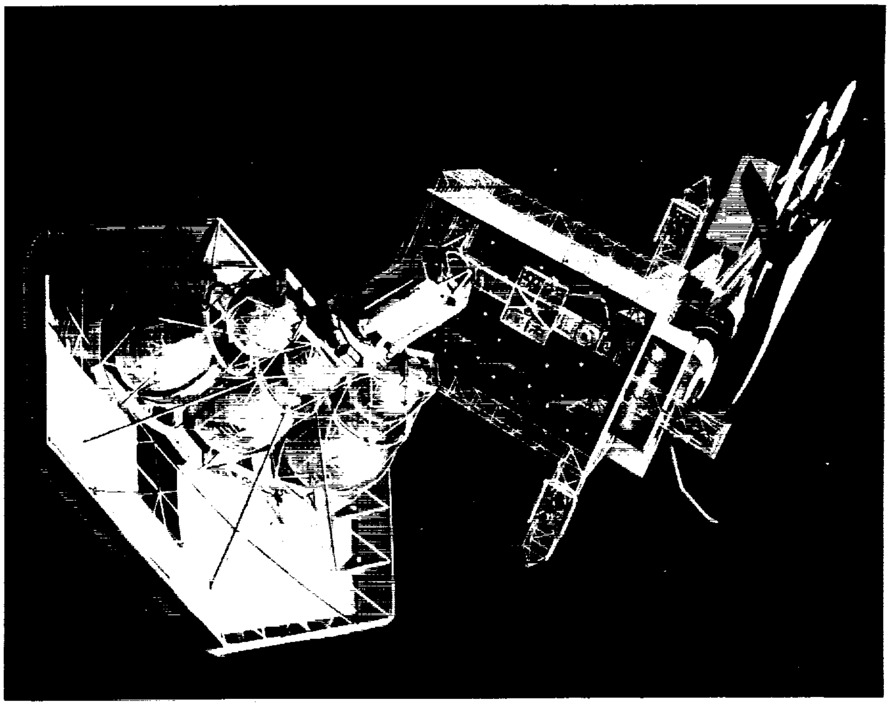
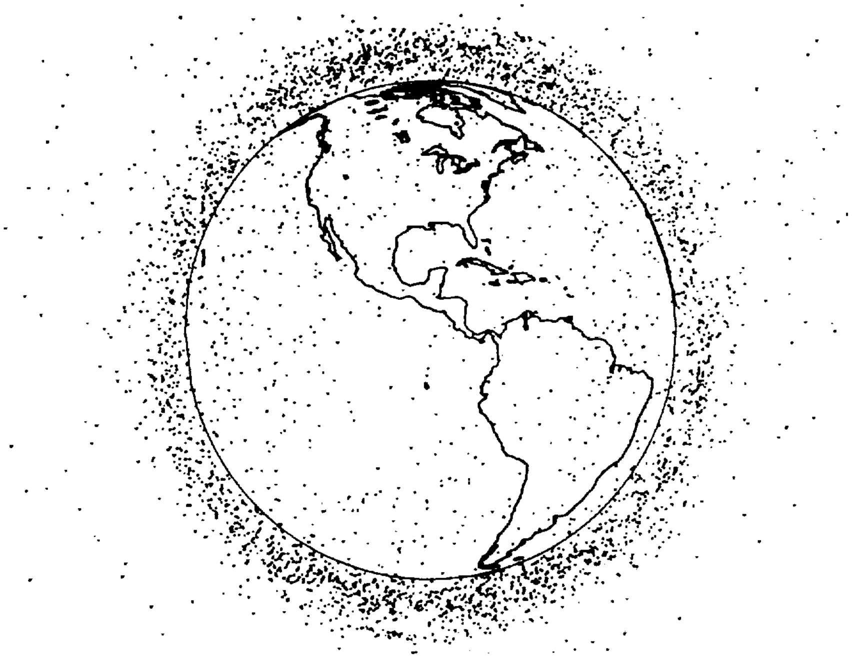


Figure 32

Space Servicing

As the hardware for complex space operations is developed, the technology for maintaining complex hardware in space must also be developed. Here is a General Dynamics concept for a space hangar and maintenance facility associated with the space station. This facility can be used to refuel, service, and repair the orbital transfer vehicle shown in the foreground.



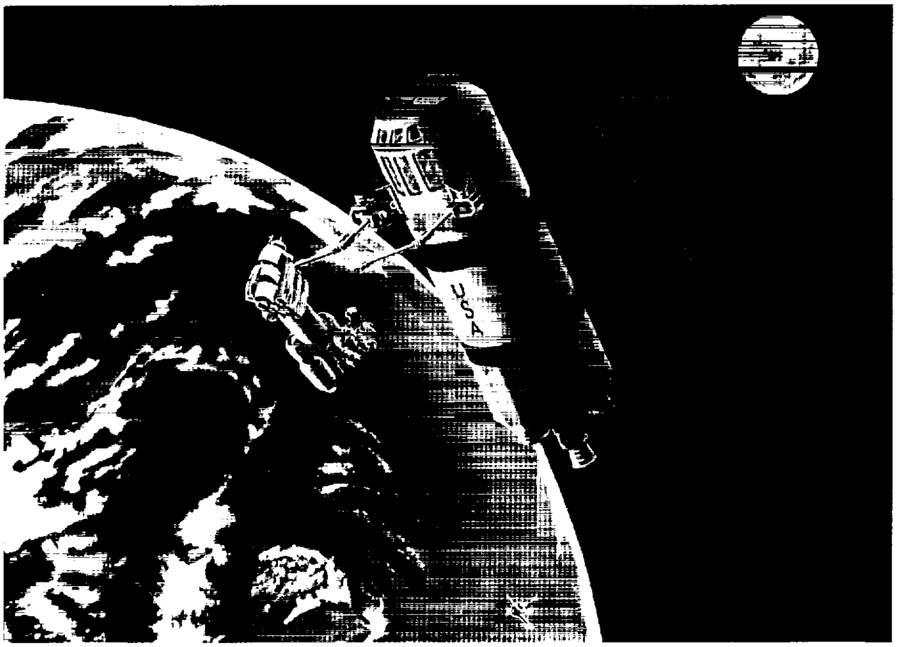


Figure 33

Orbital Debris

Orbital debris is a growing problem, which will require more and more attention as space operations increase in volume. Above is a map showing all the objects larger than 10 cm (baseball size) that were found in low Earth orbit by the U.S. Space Command on May 30, 1987. (The size of the objects is, of course, not to scale on this map; if it were, they could not be seen.) Most of these objects are spent rocket stages, dead satellites, and fragments from the breakup of old spacecraft. The map emphasizes the need to minimize new sources of orbital debris and even to clean up existing debris using "debris sweepers." A satellite designed to capture large pieces of orbital debris is shown below the map.

Artist: Ray Bruneau

program. Thirty tons of aluminum structure available at negligible cost in LEO is simply too valuable to be discarded.

Asteroid Resource Utilization

The first step in asteroid utilization is making an inventory. Advanced Earth-based observation techniques and equipment can be economically fielded to gain quantum improvements in our knowledge of the number, orbits, size, composition, and physical properties of the Earth-crossing asteroids (see table 9). A subset of those asteroids inventoried might be further examined by spaceborne instruments with capabilities similar to those of the proposed Mars geochemical mapper (see fig. 34). A smaller subset might be identified as candidates for surface exploration and pilot plant operation.

In parallel, advanced space propulsion and mission design techniques should be applied to come to understand the logistics for exploiting this potential space resource.

Space Energy Utilization

The petroleum crisis of the 1970s was not an anomalous, singular event. Even in the face of very effective energy conservation and increased petroleum exploration, the problem will return in the near future. The nearly infinite furnace of the Sun must eventually be used to provide the dominant portion of human beings' energy needs. Space is the best place to harvest and convert sunlight into more concentrated, continuous, and useful forms. Studies on the solar power satellite, a network of solar reflectors, and other means of enhancing the utility of sunlight on Earth should continue. However, the studies should be expanded to include use of such systems to provide energy from space *in* space.

Space "Real Estate" Utilization

If material and energy resources were both abundant and accessible to people, numerous human endeavors exploiting the attributes of space (nearly perfect vacuum, microgravity, and vantage point) would begin and greatly expand.

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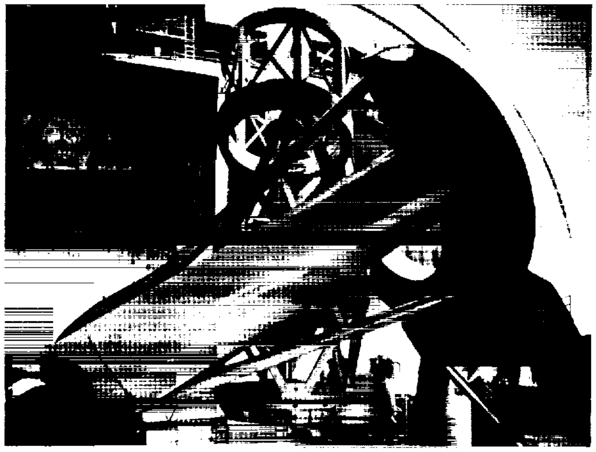


Mt. Palomar's 200-inch Hale Telescope, pointing to the zenith, as seen from the east side.

TABLE 9. *Physical Parameters of 17 Near-Earth Asteroids**

Name	*Diameter, km*	*Semimajor axis of its orbit, astronomical units*	*Orbital eccentricity*	*Inclination of its orbit, degrees from the plane of the ecliptic*
433 Eros	39.3 x 16.1[a]	1.458	0.219	10.77
887 Alinda	3.6[b]	2.50	.55	9.19
1036 Ganymed		2.66	.54	26.45
1566 Icarus	1.04[d]	1.08	.83	22.91
1580 Betulia	6.3[f]	2.19	.49	52.04
1620 Geographos	2.4[g]	1.24	.34	13.33
1627 Ivar	6.2[h]	1.86	.40	8.44
1685 Toro	5.6[i]	1.36	.44	9.37
1862 Apollo	1.2-1.5 ± 0.1[j]	1.47	.56	6.26
1865 Cerberus		1.08	.47	16.09
1915 Quetzalcoatl	0.14[h]	2.53	.58	20.5
1943 Anteros	2.0[k]	1.43	.26	8.7
2100 Ra-Shalom	>1.4[l]	0.83	.44	15.7
2201 Oljato		2.18	.71	2.5
1979 VA		2.5	.61	2.7
1980 AA		1.86	.43	4.1
1981 QA		2.35	.49	8.95

[a] Lebofsky and Rieke (1979).
[b] Zellner and Gradie (1976).
[d] Gehrels et al. (1970).
[f] Tedesco et al. (1978).
[g] Dunlap (1974).
[h] G. J. Veeder (personal communication).
[i] Dunlap et al. (1973).
[j] Lebofsky et al. (1981).
[k] Revised from Veeder et al. (1981; personal communication).
[l] Lebofsky (personal communication).

* After Lucy A. McFadden, Michael J. Gaffey, and Thomas B. McCord, 1984, Mineralogical-Petrological Characterization of Near-Earth Asteroids, Icarus **59**:25-40.

The communication relay function from GEO is only the first of an infinite series of useful and economically valuable activities in space. The ability to observe activities on Earth and, if necessary, to intervene in events may prove to be the means by which nuclear technology is reconfigured to benefit humankind rather than to threaten our existence.

Space as a place to go to and later as a place to live and work in will become of increasing importance in the decades to come. It is not too early to consider growth from NASA's 8- to 12-person space station to communities 2 or 3 orders of magnitude larger (see fig. 35). Life support technology will need to progress from merely preserving respiratory functions with some small degree of mobility for a handful of exceptional, highly trained people to providing comfortable and even luxurious accommodations for ordinary human beings at work, at school, or at leisure. (See figure 36.)

The potential of personally working and residing in space is perhaps

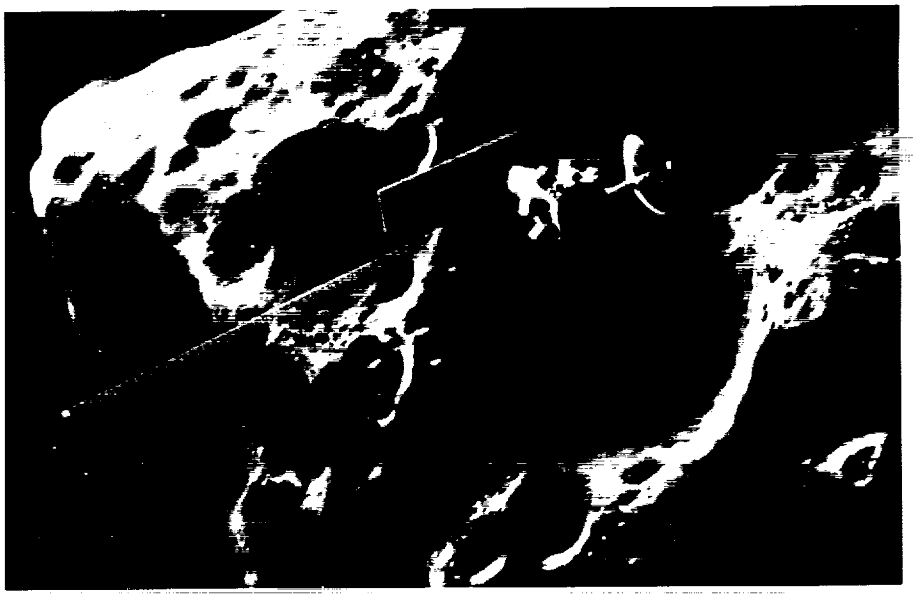


Figure 34

An Artist's Conception of an Unmanned Spacecraft Mission to an Asteroid

An unmanned spacecraft could make detailed photos of an asteroid and chemically map it in preparation for later automated mining missions.

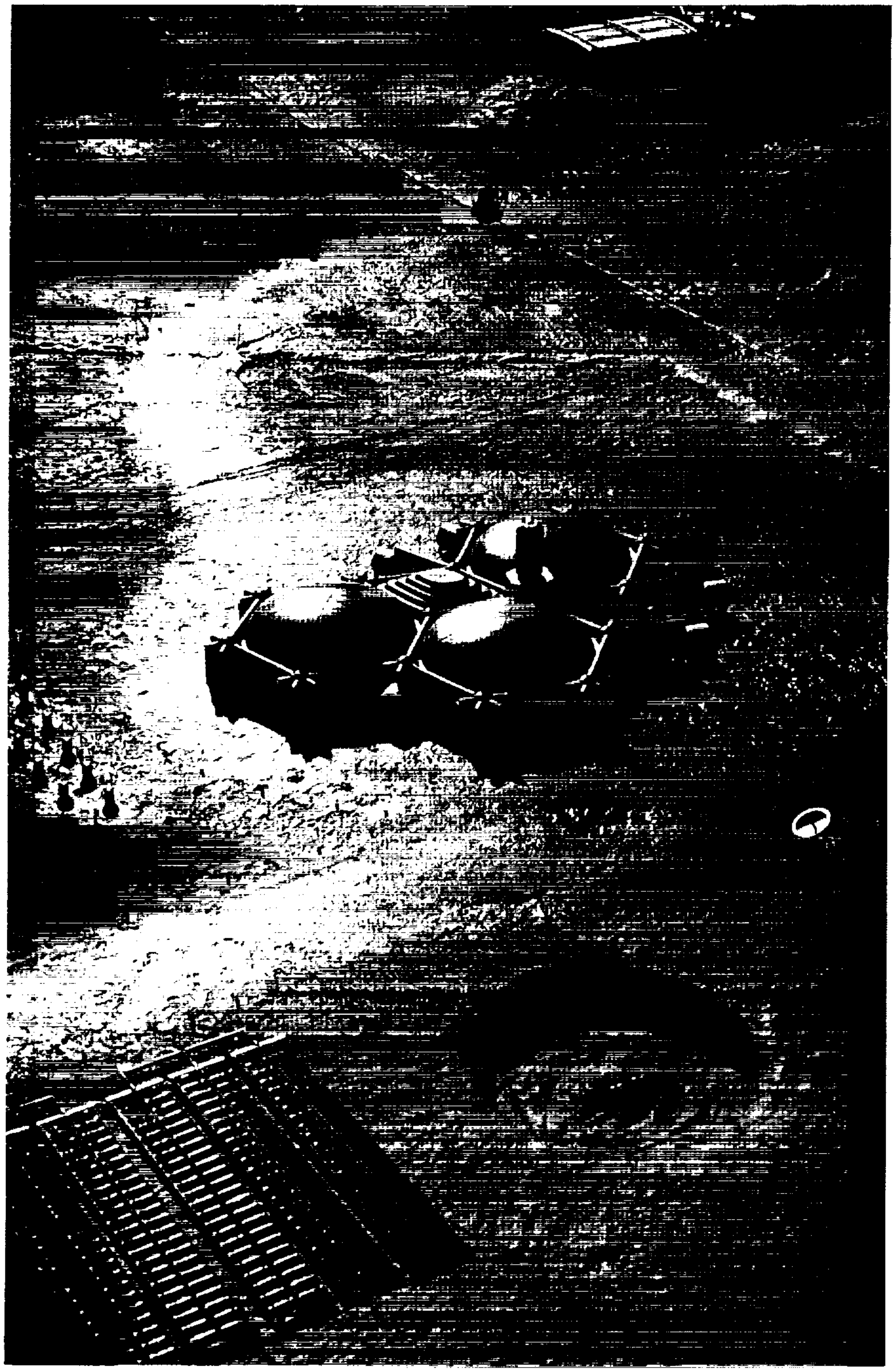


Figure 35

Architectural Model of a Moon Base

This model is the product of a recent study by a group at the University of Houston's College of Architecture. The lunar base, designed for 28 people, includes both inflatable domes and hardened modules. The three functional areas of the base are for habitation, laboratory use, and agriculture.

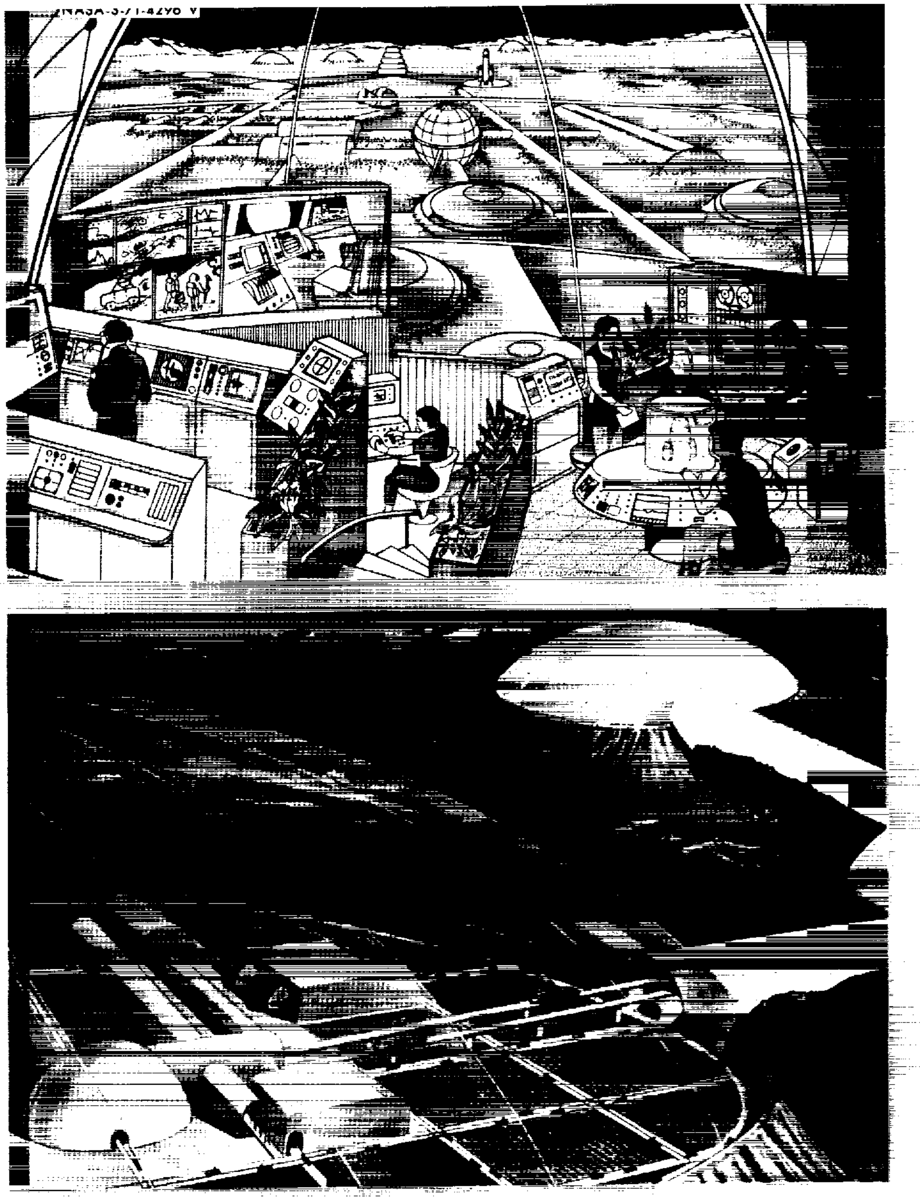
Figure 36

Advanced Lunar Bases

Eventually lunar bases will grow in both the number of people living there and the complexity and diversity of their activities.

In the top illustration, a lunar base capable of supporting several hundred people stretches out across the lunar landscape. This control center can be used to monitor various exploration and transportation activities. Residents may not be satisfied with video images or periscope views of their lunar surroundings and may, like their Mercury astronaut predecessors, insist on windows. Windows could be made thick and dense enough to provide protection from normal radiation, and lead shutters could be used during a solar flare.

In an even more advanced lunar base (bottom), large-scale networks of interconnected domes may house large farms, factories, and living areas. These domes may have Earth-like atmospheres. Currently, radiation hazards from solar flares and cosmic rays would seem to make this kind of planetary engineering for human habitation impractical, but technologies to deflect this radiation or to make humans less susceptible to it may eventually be developed to enable humans to live in large domes on the lunar surface (or on the surface of Mars).



the strongest single motivation for young people to excel. And it is important to the development of productive future generations—motivated and trained to prove totally incorrect the gloomy "fixed sum game" scenarios for humankind's future. Needed are effective and serious technical and sociological studies, artistic representation of space architectures at both small and large scale, and use of the media to portray people's future in space more realistically as productive and peaceful rather than universally warlike and destructive.

In viewing works like *Star Trek* and *Star Wars*, we must wonder what precursor society and organization *built* the wonderful artifacts so wantonly destroyed in an hour or two. Some of us would be much more interested in the character and adventures of the *builders* than we are in those of the desperate defenders and destroyers. We think many young people might share our preferences.

One final thought: A Space Academy patterned after the military academies might be a very worthwhile national investment (see fig. 37). This academy might best be a 4- to 6-year institution which took in new students who had successfully completed 2 years of undergraduate work. The last 2 or 3 years might send some of the semifinished products into distinguished universities to gain their Ph.D.s under noted scholars, scientists, and engineers who had contributed to the state of the art in space.

Congressional appointments, paid tuition and salary, assured career entry, and other attributes of the service academies should be characteristics of this institution. A generation of fully prepared people is much more important than hardware or brick and mortar.

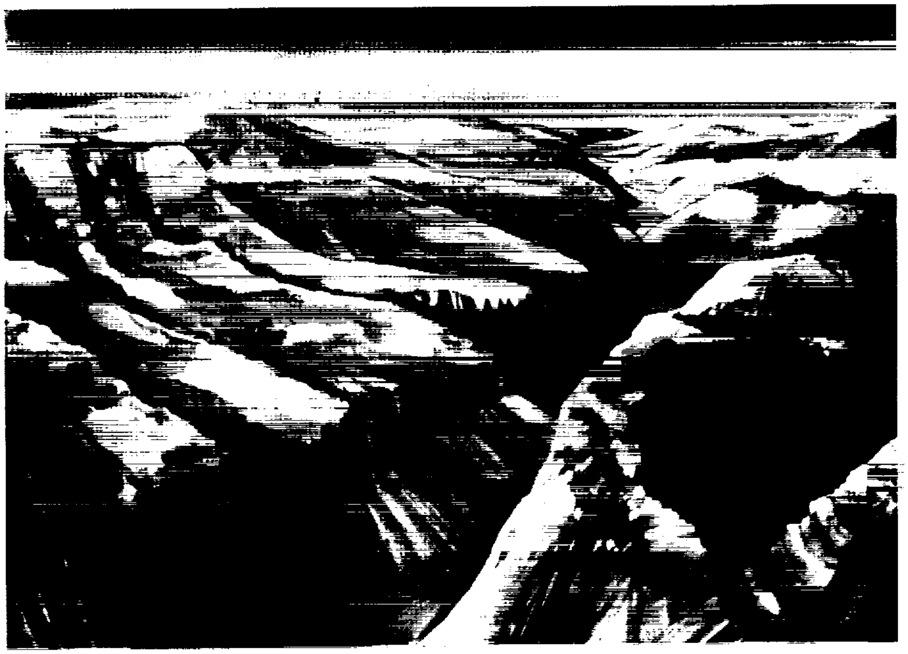
Figure 37

Space Academy

A space academy may be an effective way to prepare Americans for living and working in space. Here are views of the Air Force Academy in Colorado Springs and the graduating Air Force cadets. Graduates of a space academy would have the required technical training, the organizational training, and the motivation to be the leaders in future major space projects, including lunar base development, space infrastructure growth, and eventually Mars settlements.

Sightseeing

Other optimistic visions of the future of space activities might include extensive tourism. Here, from a scenic lookout point on Mars, is a tourist's view of the Valles Marineris, the longest, deepest, and most spectacular canyon in the solar system. The idea that much of the solar system might eventually be available for anyone to visit is clearly a visionary one, but one that is not beyond the reach of projected advances in technology.



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Addendum: Participants

The managers of the 1984 summer study were

David S. McKay, Summer Study Co-Director and Workshop Manager
Lyndon B. Johnson Space Center

Stewart Nozette, Summer Study Co-Director
California Space Institute

James Arnold, Director
of the California Space Institute

Stanley R. Sadin, Summer Study Sponsor
for the Office of Aeronautics and Space Technology
NASA Headquarters

Those who participated in the 10-week summer study as faculty fellows were the following:

James D. Burke	Jet Propulsion Laboratory
James L. Carter	University of Texas, Dallas
David R. Criswell	California Space Institute
Carolyn Dry	Virginia Polytechnic Institute
Rocco Fazzolare	University of Arizona
Tom W. Fogwell	Texas A & M University
Michael J. Gaffey	Rensselaer Polytechnic Institute
Nathan C. Goldman	University of Texas, Austin
Philip R. Harris	California Space Institute
Karl R. Johansson	North Texas State University
Elbert A. King	University of Houston, University Park
Jesa Kreiner	California State University, Fullerton
John S. Lewis	University of Arizona
Robert H. Lewis	Washington University, St. Louis
William Lewis	Clemson University
James Grier Miller	University of California, Los Angeles
Sankar Sastri	New York City Technical College
Michele Small	California Space Institute

Participants in the 1-week workshops included the following:

Constance F. Acton	Bechtel Power Corp.
William N. Agosto	Lunar Industries, Inc.
A. Edward Bence	Exxon Mineral Company
Edward Bock	General Dynamics
David F. Bowersox	Los Alamos National Laboratory
Henry W. Brandhorst, Jr.	NASA Lewis Research Center
David Buden	NASA Headquarters
Edmund J. Conway	NASA Langley Research Center
Gene Corley	Portland Cement Association
Hubert Davis	Eagle Engineering
Michael B. Duke	NASA Johnson Space Center
Charles H. Eldred	NASA Langley Research Center
Greg Fawkes	Pegasus Software
Ben R. Finney	University of Hawaii
Philip W. Garrison	Jet Propulsion Laboratory
Richard E. Gertsch	Colorado School of Mines
Mark Giampapa	University of Arizona
Charles E. Glass	University of Arizona
Charles L. Gould	Rockwell International
Joel S. Greenberg	Princeton Synergetics, Inc.
Larry A. Haskin	Washington University, St. Louis
Abe Hertzberg	University of Washington
Walter J. Hickel	Yukon Pacific
Christian W. Knudsen	Carbotek, Inc.
Eugene Konecci	University of Texas, Austin
George Kozmetsky	University of Texas, Austin
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