STRATEGIES FOR A PERMANENT LUNAR BASE

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Planned activities at a manned lunar base can be categorized as supporting one or more of three possible objectives: scientific research, exploitation of lunar resources for use in building a space infrastructure, or attainment of self-sufficiency in the lunar environment as a first step in planetary habitation. Scenarios constructed around each of the three goals have many common elements, particularly in the early phases. The cost and the complexity of the base, as well as the structure of the Space Transportation System, are functions of the chosen long-term strategy. A real lunar base will manifest some combination of characteristics from these idealized end members.

A MOON IN AMERICA'S FUTURE

The Earth is unique in the solar system, not only for harboring life, but also for its relatively massive satellite. It is speculative that the two attributes are somehow related, but certainly the Earth's companion has left cultural and biological imprints on humanity. As cumulative application of the scientific method has increased our understanding and awareness of the physical universe, fascination with the habitability of the Moon has blossomed. As late as the last century, newspaper stories reported telescopical observations of the daily lives of lunar creatures. The manned lunar landings of the last decade have dispelled such romanticism forever but in turn have provided the technology and the information necessary to fulfill a greater dream—the transport of civilization beyond the confines of the Earth.

Cultural expansion is a recurring theme in human affairs. Motivations for exploration or conquest vary from resource limitations (Mongol invasions) to religion (Turkish probings of medieval Europe) to commerce (global circumnavigations of the Sixteenth and Seventeenth Centuries). American history especially is permeated by the doctrine of manifest destiny. The concept of the frontier has come to symbolize for Americans the exercise of individual freedom, which in collective expression leads to social renewal. Contemporary popular writings cater to this mythos by describing for an overpopulated and confused world the "high frontier" of space. So far, the promise of space has been a reality for a few and only a vicarious experience for most. However, humanity, and the United States particularly, stands today at the threshold of a truly new world—the Moon.

The promise of the Moon is not immediately evident from examination of the current American space program. However, the space shuttle and the proposed space station can be viewed as building blocks in a general purpose space transportation infrastructure (Fig. 1). To service geosynchronous orbit, an upper stage is needed in addition to the shuttle. If that upper stage is provided in the form of a reusable orbit-to-orbit transfer
vehicle docked at the space station, the transportation system can be multipurpose. In particular, a rudimentary lunar transportation system then will exist because the propulsion requirements for attaining geosynchronous orbit and lunar orbit are essentially identical. A lunar landing vehicle is required to place payloads on the lunar surface, but its design can be a straightforward adaptation of the orbital transfer vehicle (OTV). The space station and the reusable OTV constitute a natural evolutionary path that, when achieved, will make accessible all near-Earth space including the Moon. This “enabling technology” is a NASA target for the mid 1990’s.

When the requisite technology exists, the American political process inevitably will include lunar surface activities as a major space objective. In fact, some sort of declaration may well precede the actual establishment of the space station. It is therefore prudent to consider the nature of a permanent manned presence on the Moon and its potential impact on the evolution of the Space Transportation System (STS).

Although the lunar base program is one in which the United States can assert its leadership in space, it is inherently international in scope and should involve as much participation as possible from other countries. Opportunities for international cooperation exist in the planning stages, in the science and technology development, and in operations at the lunar base. A legal framework will be needed to guarantee that potentially profit-making ventures adequately consider the concerns of the international community.

**USES OF THE MOON**

A manned lunar base can be discussed in terms of three distinct functions. The first involves the scientific investigation of the Moon and its environment and the application of special properties of the Moon to research problems. The second produces the capability to utilize the materials of the Moon for beneficial purposes throughout the Earth–Moon system. The last, and perhaps the most intriguing, is to conduct research and development leading to a self-sufficient and self-supporting lunar base, the first extraterrestrial human

"Figure 1. The Space Transportation System of the future may service a station in geosynchronous orbit as well as a lunar base via a station in lunar space. The lift capacity of the Shuttle fleet may be augmented by an unmanned heavy lift vehicle, designed to ship fuel and consumables to space."
colony. Although these activities take place on the Moon, the developed technology and the established capability will benefit society on Earth as well as the growing industrialization of near-Earth space.

**Scientific Research**

A lunar base will create new opportunities for investigating the Moon and its environment and for using the Moon as a platform for scientific investigations. Analogous to the function of McMurdo Base in Antarctica, the lunar base will provide logistical and supporting laboratory capability to rapidly expand knowledge of lunar geology, geophysics, environmental science, and resource potential through wide-ranging field investigations, sampling, and placement of instrumentation. Access to large, free vacuum volumes may enable new experimental facilities such as macroparticle accelerators. The firm, fixed platform will enable new astronomical interferometric measurements to be obtained (Fig. 2). The challenge of long-term, self-sufficient operations on the Moon can spur scientific and technological advances in materials science, bioprocessing, physics and chemistry based on lunar materials, and reprocessing systems. These concepts are explored by other papers in this volume.

**Exploitation of Lunar Resources**

It has been argued that major industrialization of space cannot occur without access to the resources of the Moon. Studies of immense projects such as solar power satellites

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Figure 2. A radio telescope located on the farside of the Moon would be shielded from background noise generated by terrestrial sources. Although depicted here as a parabolic dish in a convenient crater, an initial lunar instrument may well be a phased array of dipole antennas.
have demonstrated that at a sufficiently large scale, it is reasonable to develop the resource potential of the Moon to offset the high Earth-to-orbit transportation costs (Hearth, 1976). The lower gravitational field of the Moon and the absence of an atmosphere that retards objects accelerated from the surface provides a potential 20- to 30-fold advantage for launching from the Moon instead of Earth. For example, at liftoff, about 1.5% of the space shuttle’s mass is payload. Most of the mass is propellant. From the Moon, approximately 50% of the mass can be payload.

The commodity currently envisioned to be most in demand in Earth-Moon space over the next three decades is liquid oxygen, which makes up 6/7 of the mass of propellant utilized by cryogenic (hydrogen–oxygen) rockets, such as the Centaur or postulated OTV’s. Although it would appear unlikely that an atmosphereless body is a source for oxygen, it is actually an abundant element on the Moon (Arnold and Duke, 1978). It must be extracted, however, from silicate and oxide minerals into its liquid form for use as a propellant. Several processes have been suggested (Criswell, 1980) for accomplishing this, including reduction of raw soil by fluorine (which is recovered) or reduction of iron–titanium oxide (ilmenite) by hydrogen (also recovered). Preliminary laboratory studies have verified the concepts behind some of these processes.

Systems studies (e.g., Carroll et al., 1983) show that oxygen production on the Moon could benefit STS in the early years of the next century, even if the hydrogen component of the propellant needed to be brought from Earth (Fig. 3–5). Finding concentrations of

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Figure 3. Liquid oxygen fuel (LOX), manufactured on the Moon and delivered to low-Earth orbit may become a profitable export for a lunar base. A critical parameter in analyses of the system is the mass payback ratio, defined as the ratio of the excess lunar LOX in LEO to the liquid hydrogen fuel delivered from Earth to LEO.
water at the lunar poles (Arnold, 1979) or extracting the dispersed solar wind–derived hydrogen in the lunar regolith would greatly improve the economics of the transportation system.

Other commodities also could be produced. Metals, such as iron or titanium, can be extracted from the lunar soil or from specific rocks or minerals with differing degrees of difficulty. For example, small quantities of metal (primarily iron) from meteorites can be concentrated with a magnetic device from large amounts of lunar soil, or, with much larger energy inputs, titanium can be obtained from ilmenite. These products could find applications in large space structures. Lunar titania or alumina might be used to produce aerobrakes (heat shields) used in OTV’s. In the long term, at relatively high levels of development, production of components for solar electric power generation in space (e.g., solar power satellites) could be made feasible (Bock, 1979).

Lunar Autarky

A self–sufficient lunar base is a possible long–term objective that creates new challenges in planning and development. In the near term, emplacement of a controlled environment capsule on the Moon involves known technology. The initial concept for a lunar habitat module is simply an extension of the design experience from Apollo, Skylab, the space shuttle, and space station (Fig. 6). A different perspective is required to plan systems that can utilize the Moon’s native materials and energy sources to produce a self–sufficient capability.

Most of the generic technologies for an advanced system are similar to those employed in general space operations (life support, power, thermal control, communications, logistics, and transportation, etc.), but they must be modified to utilize lunar materials for growth and extension. Ultimately, the desire to minimize or to eliminate the resupply link from
Earth requires a host of applications, new to the space program, carried to new levels of system reliability. Exploration of technologies such as lunar metallurgy, ceramics, manufacturing processes, power systems, and others, will reveal whether autarky is a realistic objective and can prepare the way for achieving it at an operational base. Perhaps this is the most compelling rationale for a lunar base program, as it promises eventual self-sufficiency elsewhere in the solar system.

PHASED EVOLUTION OF A LUNAR BASE

We loosely define three scenarios, each based on one of the long-term rationales described above: scientific research, production, and self-sufficiency (Tables 1–3). Each scenario passes through several phases, some of which are common to the other scenarios. The distinction among the three views lies with the culminating phase of each.

Precursor Exploration. Because the scientific data base is incomplete, particularly in the polar regions, the first step in Phase I is global mapping of the Moon, both with relatively high resolution imagery and with remote-sensing measurements to determine
the chemical variability. This task can be accomplished with an unmanned satellite, a Lunar Geochemical Orbiter, or LGO (Minear et al., 1977), which is a proposed mission in NASA's planetary program and could be flown in the 1990–1992 time frame. The LGO is in the Planetary Observer mission class, a low-cost approach to planetary exploration recommended by the report of the Solar System Exploration Committee (1983). Secondly, Phase I should include research on technologies necessary to exploit lunar resources. Technology development in resource problems on Earth is typically a long lead time process. At the conclusion of Phase I, the initial site for a base will have been defined and planned activities understood in some detail. Concurrently with this preliminary phase in the lunar program, development of a space station and an OTV capable of supporting a lunar base would be carried out in NASA's STS program.

Research Outpost. At Phase II, an initial surface facility would establish limited research capability for science, materials processing, or lunar surface operations. Depending on the long-term objectives of the lunar base program, the detailed studies and the experimental plans start to diverge at this phase for the different scenarios. A focus on lunar science and astronomy would result in local geological exploration, the establishment of a small astronomical observatory, and emplacement of automated instruments. If production were to be the focus, a pilot plant for lunar oxygen extraction could be set up instead, and study of the fabrication of aerobrakes from lunar material could be initiated. If the program goal pointed to achieving self-sufficiency, the emphasis at this stage could be on agricultural experiments utilizing lunar soil as substrate and recycling water, oxygen, and carbon dioxide.

To accomplish Phase II in any of the scenarios, the STS must have the capability of landing and taking off from the Moon, transporting manned capsules (about 10,000 kg) to and from the lunar surface, and delivering payloads of about 20,000 kg to the
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Table 1. Lunar Base Growth Phases: Science Base Scenario

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<th>Phase I: Preparatory exploration</th>
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<tr>
<td>• Lunar orbiter explorer and mapper</td>
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<tr>
<td>• Instrument and experiment definition</td>
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<tr>
<td>• Site selection</td>
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<td>• Automated site preparation</td>
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<th>Phase II: Research outpost</th>
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<td>• Minimum base, temporarily occupied, totally resupplied from Earth</td>
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<tr>
<td>• Small telescope/Geoscience module</td>
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<td>• Short range science sorties</td>
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<td>• Instrument package emplacement</td>
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<th>Phase III: Operational base</th>
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<td>• Permanently occupied facility</td>
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<tr>
<td>• Consumable production/Recycling pilot plant</td>
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<tr>
<td>• Longer range science sorties</td>
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<tr>
<td>• Geoscience/Biomedical laboratory</td>
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<tr>
<td>• Experimental lunar radiotelescope</td>
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<td>• Extended surface science experiment packages</td>
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<th>Phase IV: Advanced base</th>
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<tr>
<td>• Advanced consumable production</td>
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<tr>
<td>• Satellite outposts</td>
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<tr>
<td>• Advanced geoscience laboratory</td>
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<tr>
<td>• Plant research laboratory</td>
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<tr>
<td>• Advanced astronomical observatory</td>
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<td>• Long-range surface exploration</td>
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lunar surface. This involves delivering approximately 40,000 kg into lunar orbit using OTV’s. The requirement for storage of the return vehicle on the Moon for extended periods (14 days to 3 months) may require new high-performance, storable propellant systems at this phase of development.

*Permanent Occupancy.* At Phase III, permanent occupancy is the objective. The surface infrastructure would include greater access to power, better mobility in and away from the base, and more diversified research capability. Still, depending on the long-term objectives, the nature of the base can vary. A science base might emphasize long-range traverses for planetological studies or extension of observational capability with larger telescopes. A production base will incorporate highly automated systems to produce and transfer liquid oxygen for use in the transportation system. Advanced research for a self-sufficient base would be making the first extensions of the base utilizing indigenous materials. The production and the self-sufficiency scenarios require a small cousin to
Table 2. Lunar Base Growth Phases Production Base Scenario.

A lunar base that is intended to develop one or more products for commercial use. Manned activity may be continuous, but a high degree of automation is expected.

Phase I: Preparatory exploration
- Lunar orbiter explorer and mapper
- Lunar pilot plant definition
- Site selection
- Automated site preparation

Phase II: Research outpost
- Minimum base, temporarily occupied, totally resupplied from Earth
- Surface mining pilot operation
- Lunar oxygen pilot plant
- Lunar materials utilization research module

Phase III: Operational base
- Permanently occupied facility
- Expanded mining facility
- Consumables supplied locally
- Oxygen production plant
- Lunar materials processing pilot plant(s)

Phase IV: Advanced base
- Large scale oxygen production
- Ceramics/Metals production facility
- Locally derived consumables for industrial use
- Industrial research facility

the Earth-orbit space station in lunar space (lunar orbit or an Earth-Moon libration point) to provide for transfer, refueling, and maintenance of the lunar lander and the OTV's.

Advanced Base. The advanced base, Phase IV, is even more specialized. Depending on the long-term plan, it produces more types or a greater range of scientific investigations, adds products to the growing lunar industrial base, or enters a phase of significant expansion of capabilities using lunar materials as the majority of the feedstock. This is the terminal phase for the science and production scenarios. Future growth may occur by enlarging the number of experiments or products produced on the Moon, but a self-sustaining capability is not included. The production base might even develop toward a highly automated state where permanent occupancy was unnecessary. For the production and independence scenarios, the base should begin paying its own operational costs. In the self-sufficiency scenario, research and development of pilot plants aimed at a broad range of indigenous lunar technologies would be pursued. The final phase of the self-sufficient scenario is a truly autarkic settlement, a lunar colony, in which the link to Earth can be discretionary.
**Lunar Base Concepts**

Table 3. Lunar Growth Phases: Lunar Self-sufficiency Research Base Scenario

A lunar base that grows in its capacity to support itself and expand its capabilities utilizing the indigenous resources of the Moon, with the ultimate objective of becoming independent of Earth.

Phase I: Preparatory exploration
- Lunar orbiter explorer and mapper
- Process definition
- Site selection
- Automated site preparation

Phase II: Research outpost
- Minimum base, temporarily occupied, totally resupplied from Earth
- Surface mining pilot operation
- Lunar oxygen production pilot plant
- Closed systems research module

Phase III: Operational base
- Permanently occupied facility
- Expanded mining facility
- Lunar agriculture research laboratory
- Lunar materials processing pilot plant(s)

Phase IV: Advanced base
- Lunar ecology research laboratory
- Lunar power station-90% lunar materials-derived
- Agricultural production pilot plant
- Lunar manufacturing facility
- Oxygen production plant
- Lunar volatile extraction pilot plant

Phase V: Self-sufficient colony
- Full-scale production of exportable oxygen
- Volatile production for agriculture, Moon-orbit transportation
- Closed ecological life support system
- Lunar manufacturing facility: tools, containment systems, fabricated assemblies, etc.
- Lunar power station-100% lunar materials-derived
- Expanding population base

**EVOLUTION OF THE PROGRAM**

Figure 7 ties the possible development of a lunar base to the growth of lunar resource support of the transportation system. Initially, the base is totally dependent on terrestrial supply where 7 kg in low-Earth orbit is required to place 1 kg on the lunar surface. With the introduction of lunar oxygen first into near-Moon operations and then into the return leg of the transportation system, the slope of the curve changes from 7:1 to 3.5:1.
As the lunar manufacturing capability increases to the point where aerobrakes can be manufactured, the slope decreases to something slightly greater than 1:1. Further growth of lunar capability allows expansion of base mass to be more or less independent of the quantity of imported terrestrial mass. At the point of self-sufficiency, only trace minerals and crew changeout are chargeable weights to lunar operations; the slope of the curve in Fig. 7 is essentially flat.

Another consideration in the growth of lunar activities is the economic “balance of trade” between Earth orbit and the lunar surface. The value of lunar products may support lunar operations before a true mass balance is achieved. It is difficult to calculate the economic value of lunar oxygen and other products in low-Earth orbit. However these “lunar credits” are shown qualitatively in Fig. 7 at the point where a closed ecological life support system (CELSS) and a significant manufacturing capability are available. The slope of the “credits” line will be a function of many things, such as the amount of oxygen required to support non-lunar activities, the value and quantity of lunar resources required in low-Earth orbit, and the more intangible value of science and research enabled by the lunar base. Finally, the dashed line of constant slope indicates the continued total dependency that would exist if these technologies are not pursued on the Moon, that is, if a self-sufficiency element is not included in the lunar base program.
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The real lunar base will evolve as some combination of the above scenarios. Determination of the right mix requires research, development, and debate. Even if a program is started now, several years should be devoted to study of the detailed lunar base scenario. The time is available because the development of the space transportation infrastructure and the completion of the orbital science survey will take 7–10 years. Proper preparation will make it possible to decide on a specific lunar base design in the early 1990’s. That time frame is consistent with the development of the infrastructure that will enable the lunar base program to be carried out to its full potential. The first manned landings could occur early in the first decade of the next century; permanent occupancy could be achieved by the year 2007, the fiftieth anniversary of the Space Age.

There are potential technological problems that may slow the development of the lunar base, and at each phase there will be serious questions as to whether to proceed and how and when to proceed. A commitment need not be made now to the whole plan. Nevertheless, the long-term objective is one of immense significance in human history and should not be casually discarded. It is inevitable that humankind will settle the Moon and other bodies in the Solar System. We live in a generation that has already taken very significant steps along that path. With careful planning, we can nurture the capability to move from the planet, to provide benefits to the Earth, and to satisfy humanity’s spirit of adventure.

REFERENCES