2 / LUNAR BASE CONCEPTS

THE TERM "LUNAR BASE" can refer to a spectrum of concepts ranging from a mannable "line shack" to a multifunctional, self-sufficient, populous colony. In general, the authors contributing to this book discuss the earliest stages of a permanently manned facility with the capability for scientific investigations and some ability to support its own operation with local materials. The exact form of the "final" configuration usually is not critical to the discussion until cost is included. Costs of a lunar base can be similar to the space station program or can be at the level of the Apollo project. Since cost is such a sensitive topic in the advocacy phase, it becomes very important to understand not only the total cost but also the spending rate and the basic assumptions about what is charged to the project. The costs derived by Hoffman and Niehoff in their study presented in this section differ from costs referenced by Sellers and Keaton in a later section. The final configurations in the two studies differ considerably, but in both cases the spending rates over the duration of the project are well within the rate of expenditure of the current space program and are substantially less than rates associated with Project Apollo.

Because lower cost is a major strategy goal, design concepts generally adopt hardware from prior programs. For example, the studies conducted by NASA in the 1960's and described by Lowman and by Johnson and Leonard depict habitats inspired by the Apollo transportation system. Contemporary drawings show space station modules emplaced on the lunar surface. Maximizing design inheritance to decrease uncertainties in technology development builds confidence in estimates of feasibility and affordability of a lunar base or any other program. Conversely, awareness of a long range lunar goal during design of the space station can increase the "inheritability" of the technology. Duke *et al.* propose a model for long range development based on three distinct choices for programmatic objectives.

The selection of the location for the first base on the Moon will be heavily influenced by programmatic priorities. Some argue that a return to one of the Apollo landing sites will suffice. The geology and the environment of a landing site are well known, obviating the need for any expense or delay associated with precursor

survey missions. If scientific investigations have the highest priorities, then the major questions in lunar science would drive the selection process. Since radio astronomy from the farside of the Moon has long been a prime candidate for a surface investigation, a good location might be somewhere on the limb, where communication with the Earth can be maintained while the radio telescope is still nearby. On the other hand, the long-term strategy for building the surface infrastructure might require the early exploitation of local resources. An unmanned polar orbiting satellite would make sense as a precursor resource survey mission.

Some scientists have advocated a base at a lunar pole. The nearly perpendicular orientation of the lunar rotation axis to its orbital plane results in a continual twilight at the poles and, consequently, constant access to solar energy. A polar base would reside on the limb and would be continuously accessible from a station in lunar polar orbit. Unfortunately, the polar regions are the least known either in terms of geology or resources. Jim Burke reviews the difficulties and advantages of polar living in more detail and presents some concepts for exploiting that unique environment.

Lunar bases at any other latitude will suffer through the diurnal cycle of two weeks of daylight followed by two weeks of night. A power system based entirely on solar energy will require massive energy storage facilities for night-time usage and must be oversized to generate the stored energy during the daytime operation. Principally for this reason, nuclear energy appears to be the best solution for early stage lunar bases. Buden and Angelo discuss the evolution of the power plant with growing needs at the base, while French reviews some practical considerations of siting nuclear reactors on the Moon.

LUNAR BASES: A POST-APOLLO EVALUATION

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A lunar base would be an extremely productive choice for future American space efforts. Further exploration of the Moon is scientifically important; the Moon offers a stable and radio-quiet platform for astronomy and space physics, material resources (chiefly Si, Al, Fe, O, Mg, and Ti) are available for use in near-Earth space or on the Moon itself, and Earth-Moon operations offer the technological stimulus of interplanetary missions at lower cost and with less risk. It is recommended that the Lunar Geochemical Orbiter be given high priority, that space station modules be designed for use on the Moon as well as in space, that design studies of a manned orbital transfer vehicle be started, and that continued analysis of lunar samples and meteorites be strongly supported.

INTRODUCTION

The Apollo Program, whose six lunar landing missions began at Tranquillity Base, could have led to the establishment of a permanent base on the Moon. It did not, for reasons that are well documented, and there have been no American lunar missions of any sort since 1972. However, with the revival of the American space program, marked by the first flight of the space shuttle in 1981, has come a revival of interest in lunar and planetary missions in general. The Solar System Exploration Committee (1983) has recommended an ambitious but fiscally conservative set of missions that is now being acted upon, the first two new starts being the Venus Radar Mapper and the Mars Observer. A parallel development has been renewed interest in lunar bases (Duke *et al.*, 1984), demonstrated by the 1984 Lunar Base Symposium held in Washington and its preparatory workshop held in Los Alamos.

This paper was presented at the 1984 symposium in abbreviated form. Its objective is to reevaluate the desirability of an American lunar base in light of the many scientific, technological, and political developments since the last Apollo mission in 1972. The term "lunar base" will be used here to cover a wide range of possible programs, from small facilities for short-term occupations by a few people up to large complexes at several locations occupied semi-permanently by large staffs. It will not include large autonomous colonies on the Moon, since one of the objectives of a lunar base program would be to explore the technical and economic feasibility of such colonies.

BACKGROUND

Technically sound and essentially modern descriptions of possible lunar bases were published as early as 1946 (Harper, 1947; Clarke, 1951; von Braun *et al.*, 1953; Burgess, 1957). Detailed planning for such bases began in the United States shortly after the Apollo

Program was started in 1961, and dozen of studies were carried out by NASA, its contractors, the U.S. Air Force, and other organizations. A biliography of these studies has been compiled by Lowman (1984), but only a few main concepts can be summarized in this paper.

The great majority of lunar base concepts proposed in the 1960s were predicated on use of the Saturn V system or direct derivatives thereof. Two of these, the Apollo Logistics Support System (ALSS) and Lunar Exploration Systems for Apollo (LESA), are illustrated in Figs. 1 and 2. The LESA was the most ambitious base proposal of the 1960s,

Figure 1. Artists' concepts of ALSS and LESA with comparative statistics. From Anonymous (1964).

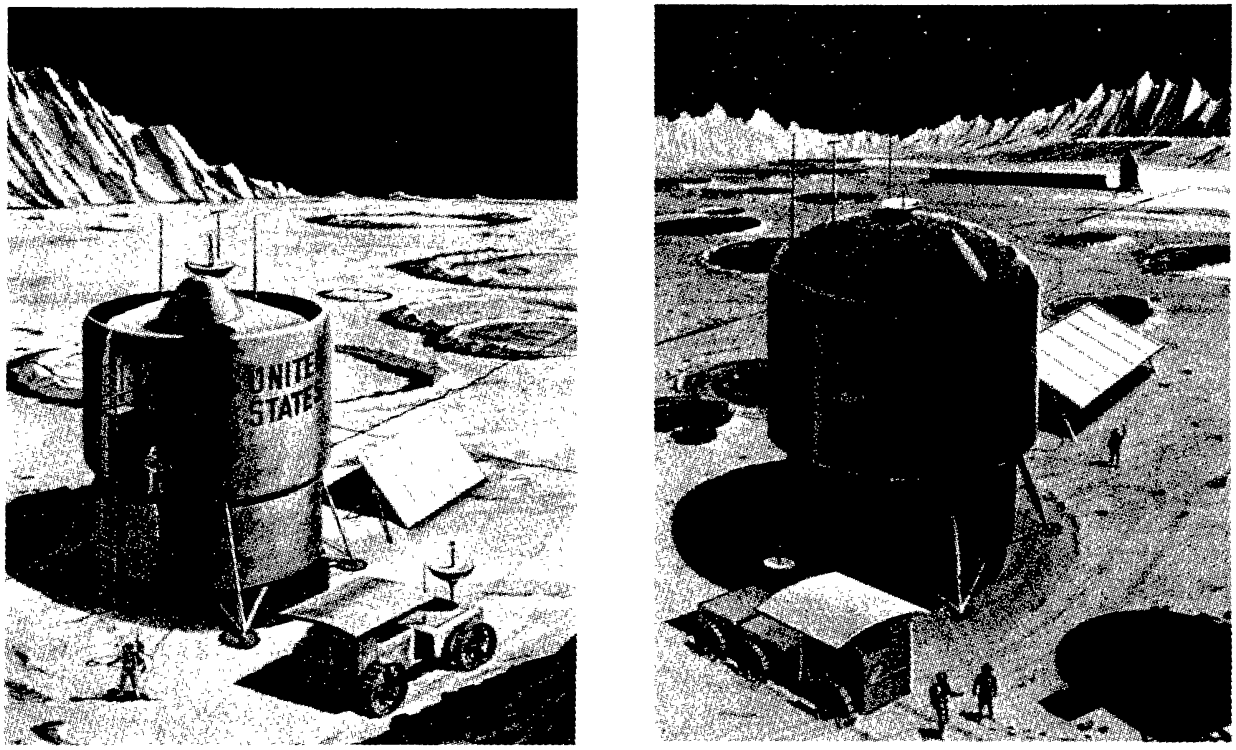

Figure 2. Two versions of LESA modules emplaced on the Moon. From Boeing (1963).

being planned for expansion by landing of separate 25,000-lb. modules. The LESA could have formed the nucleus for a large permanent colony had it been carried out. A complete set of supporting parametric studies was concluded by various contractors, covering all aspects of base establishment and operation, including logistics, life support, and scientific missions. Some aspects of the LESA studies are by now quite outdated, and the Saturn V system is no longer available. The missions proposed for LESA have now been carried out to some extent by the Apollo Program or, for Moon-based astronomy, by instruments in Earth orbit. Nevertheless, the surface environmental model assumed was fundamentally correct and the life-support parameters reasonably accurate. It seems safe to say that the LESA studies are still of value for baseline planning of future lunar programs.

Probably the most important lunar base study in terms of possible future work is the Lunar Base Synthesis Study, completed in 1971 by North American Rockwell (1971a). This study is of interest in several respects. First, it was done late enough to take into account results from early Apollo missions, to say nothing of experience gained from the many Earth-orbital missions flown by then. Second, it was the only major lunar base study done to assume use of transportation to low Earth orbit by the space shuttle rather than the Saturn V. The study produced a conceptual design for crew modules (Fig. 3) derived from a related study of an orbiting lunar station (North American Rockwell, 1971b) that could be used either for a modular space station or a lunar surface base. It is clear that if a lunar base program should be started by the U.S. within the next 10 years, something like the 1971 studies must be the starting point, given the continued use

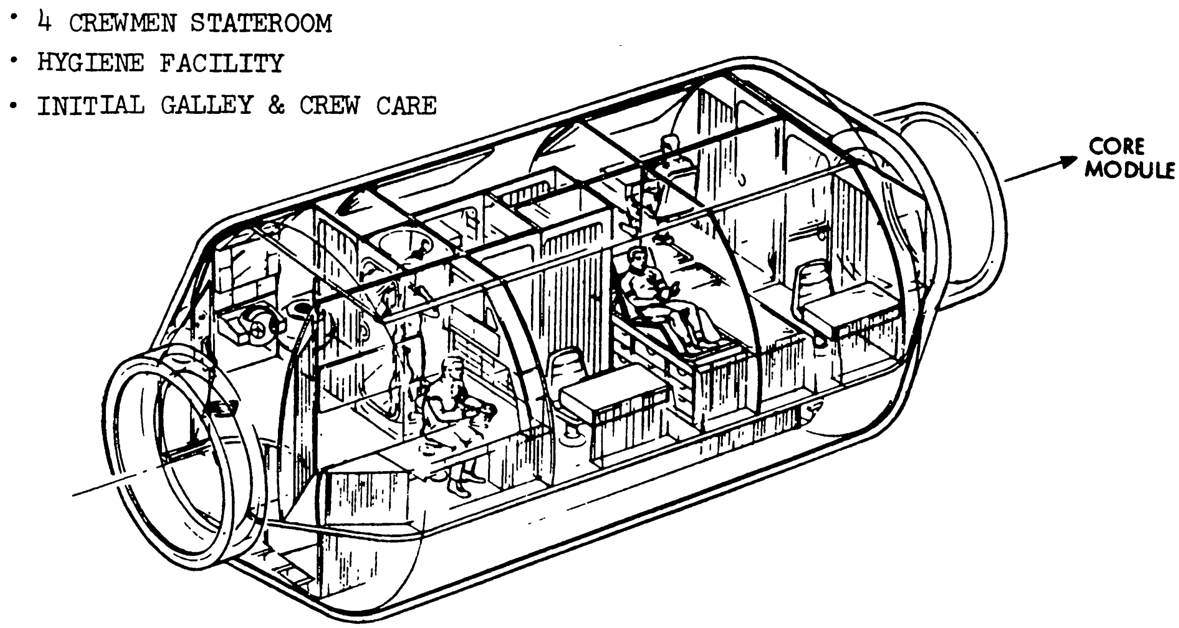

Figure 3. Module for a lunar surface base (LSB) derived from a modular space station (MSS) module designed for shuttle launch. From North American Rockwell (1971a).

of the space shuttle and the presumed establishment of a permanent space station in low Earth orbit.

A large number of studies was carried out in the 1960s on the nature and use of lunar resources, many of which are still of value. For example, lunar soil has proven easily workable, so parametric studies involving its bulk use for shielding are still applicable. One important exception, however, relates to the use of indigenous lunar water. Many studies, some published as late as the month before the Apollo 11 mission (Lowman, 1969), assumed that lunar rocks would contain at least a small amount of combined water that could be extracted for life support or, optimistically, for use as rocket fuel. Unfortunately, it was discovered immediately on return of actual lunar samples that at least the surficial rocks and soils are completely anhydrous. Even more discouraging is the fact that all lunar igneous rocks, such as basalts, are highly reduced in a chemical sense, implying extremely dry magmas and magma source areas. In this respect the early lunar base studies appear to have been optimistic, although the possibility of deep-seated lunar water or hydrogen, or even polar ice (Arnold, 1979; O'Keefe, 1985), cannot be ruled out completely.

It is clear that a substantial fraction of the work on possible lunar bases done before 1972 has permanent value and should be taken account of in any planning for new lunar programs. Let us now consider factors that have changed greatly since 1972.

POST-APOLLO DEVELOPMENTS RELEVANT TO LUNAR BASES

Several developments and trends since 1972 have direct importance for the lunar base concept and must be taken into account in a reevaluation such as future lunar operations and missions.

Resumption of U.S. Planetary Exploration

After a period of several years in the 1970s when no new starts were approved, the United States has resumed a modest program of planetary missions, starting with the Venus Radar Mapper. The VRM is the first element of a long-term planetary program outlined by the Solar System Exploration Committee (SSEC, 1983) and utilizes relatively low-cost common hardware. The program includes a Lunar Geoscience Orbiter as one priority item, reaffirming the scientific value of renewed lunar exploration.

Space Transportation System

The fundamental inefficiency of the "ammunition philosophy," *i.e.*, expendable boosters, was always obvious despite the success of the Saturn V-launched Apollo missions. With the successful development of the space shuttle, the U.S. is now back on what should eventually be a more cost-effective course of manned space exploration. The shuttle now provides routine and frequent access to low Earth orbit (LEO). Furthermore, the last lunar base study performed before 1972 (North American Rockwell, 1971a) showed that the shuttle could carry space station modules adaptable to use on the lunar surface.

Space Station

The permanent manned space station, a traditional space goal, has now become an official U.S. program, and Phase B studies have begun. The basic feasibility of such a station is unquestioned, although support for it has been less than unanimous. Given its relatively low cost and operational utility for satellite servicing and microgravity manufacturing, the space station in some form should be in orbit by the 1990s. Once deployed, it can serve as a transportation node, one function being to launch lunar and planetary missions. The space station will then be another link in a space transportation system that could establish and support a lunar base. Furthermore, two related studies on a lunar base and an orbiting lunar station (North American Rockwell, 1971a,b) called attention to the possibility of designing space station modules for use with minor modifications on the Moon as well. It thus appears that the only major items necessary for a lunar base not already in use or being planned are a reusable orbital transfer vehicle (OTV) and a comparable lunar landing vehicle (LLV).

Assimilation of Apollo Scientific Results

Although study of the 385 kg of returned lunar samples can profitably continue for many years with increasingly refined or completely new analytical techniques, it is safe to say that the scientific results of the Apollo Program have now been largely assimilated (French, 1977; Taylor, 1982). With respect to a lunar base, our knowledge of the Moon, although incomplete in many respects, is now comprehensive and firm enough to say that the environmental feasibility of such a base is established. The surface environment, the dominant topography, and the gross composition of the main crustal rocks are all known well enough to permit detailed planning for at least a temporary lunar base supporting perhaps a few dozen people. The feasibility of a permanent autonomous colony, of course, is at this time far from established.

General Technical Progress

It is hardly necessary to point out that there has been great progress since 1972, in space technology as well as in several other fields, all having some bearing on lunar base feasibility. Among the most obvious are remote sensing, rocket propulsion, telemetry, materials, communications, and computer technology (Lowman, 1979). The field of microelectronics in particular has advanced several generations since 1972, its most spectacular application being in the small but powerful computers of the mid 1980s. Even a cursory review of such technological progress would be out of place here; it is mentioned simply to point out that lunar base concepts that would have been feasible with the technology of 1970 will obviously be far more so with the technology of the 1990s. It is worthwhile citing here an historic analogy: the 1927 New York-to-Paris flight of Charles Lindbergh. What had been accomplished marginally and with great difficulty in 1919 by Alcock and Brown, who barely managed to fly from Newfoundland to Ireland, was technically fairly easy for Lindbergh eight years later because of the rapid improvement in aircraft and especially aircraft engines.

Reorientation of the Earth Sciences

From about 1965 to the early 1980s terrestrial geology and geophysics were dominated by plate tectonics. Plate tectonic theory is fundamentally concerned with oceanic crust and its margins (past and present), and its deserved acceptance led to a certain eclipsing of interest in studies of the continental crust. This imbalance is starting to correct itself, and there has been a strong revival of research in purely continental geology and geophysics. Particularly relevant in the context of this paper is the growing number of studies of early crustal genesis, focused on Precambrian shields and the lower continental crust as revealed by reflection profiling. The study of lunar geology has already had influence on concepts of continental crust formation (Lowman, 1976; Frey, 1980; Solomon, 1980) by demonstrating early global differentiation in even a small body. Many questions remain, however, about the early evolution of the Earth; and detailed exploration of the Moon, particularly the highlands, will certainly contribute to our understanding of the Earth.

Soviet Space Operations

Although the United States was the first to land men on the Moon, the Soviet Union has continued its long tradition of ambitious and persevering efforts in astronautics that began in the 1930s and is reportedly developing new launch vehicles far more capable than the American shuttle. Several Salyut space stations have given the Soviet Union unique experience with long-duration manned spaceflight. There has been considerable speculation about the next direction of Russian space activities; one informed view (Schmitt and Silver, 1984) is that the U.S.S.R. will attempt a manned Mars mission (though not necessarily a landing) in the early 1990s. However, a Russian lunar program seems equally possible, one indication being the recent announcement of a lunar polar orbiter to be launched late in this decade. The late Charles Sheldon, Library of Congress authority on Soviet space programs, wrote (1967) that colonization of the entire habitable solar system was the probable ultimate goal of Russian space ventures. Viewed in this context, the

Moon can be considered the most easily accessible and "habitable" extraterrestrial body. The justification for a lunar base will be as valid for the Soviet Union as for the United States, which is a factor that must be considered in planning post-space station American programs.

THE NEED FOR A LUNAR BASE: 1985

The desirability of a lunar base was repeatedly asserted during the Apollo Program. But the very success of that program and of other space activities raises the possibility that formerly proposed lunar base functions and objectives have already been accomplished or can be better accomplished in other ways. The question can be conveniently discussed under the following headings.

Unanswered Scientific Questions

The Apollo missions and several years' analysis of data and samples therefrom have obviously settled many pre-Apollo controversies about lunar geology (Taylor, 1982). However, as had been expected (Lowman, 1966a), an even greater number of new questions have been raised. Most general is the question of how the Moon formed; even 15 years after Apollo 11 there appear to be insuperable difficulties with all traditional theories. The composition and structure of the highland crust are only approximately known, and there is consequently strong disagreement on whether it formed by differentiation in a magma ocean or by partial melting and subsequent igneous activity. The mare basins are now agreed to be large basalt-flooded impact craters, but it is not known whether they were formed by a discrete late heavy bombardment or as part of a continuously declining flux. Furthermore, the source and nature of the basin-forming bodies, a key problem in solar system evolution, are quite unknown. The question of whether the Moon is still internally active is as yet unanswered. If it is, and if volatiles such as water or hydrogen are being emitted, the answer has extremely important implications for the ultimate habitability of the Moon.

Moon-based Astronomy

The spectacular success of Earth-orbiting astronomical satellites and the hoped-for success of the forthcoming Hubble Space Telescope raise the obvious question of whether the traditional goal of an observatory on the Moon is still worth pursuing. The answer appears to be an unequivocal "yes" for two main reasons. First, the existing and planned Earth-orbiting telescopes are heavily over-subscribed; there are far more important observations to be made than these instruments can accommodate. Second, the Moon has unique advantages over any instrument in Earth orbit, as summarized by Walker (1984). The farside offers shielding from terrestrial radiation, and in particular is probably the most radio-silent location in the accessible solar system. The Moon offers a slow rotation rate for continuous observations up to 14 days long, as well as a stable platform for interferometry. Finally, it may also be a good place for observation of neutrinos and gravity waves; an attempt was actually made during the Apollo 17 mission to detect

gravity waves (Giganti *et al.*, 1972). In summary, it appears that Moon-based astronomy can still provide much of the scientific justification for a lunar base.

Stimulus to Space Technology

The Apollo Program proved to be, as had been hoped, an immense stimulus to technology in fields far removed from the obvious ones, such as rocket propulsion and inertial guidance (Lowman, 1975). However, it also gave the U.S. a commanding, though perhaps temporary, lead in space technology. Rocket engines using cryogenic hydrogen and oxygen, for example, are in routine use in the space shuttle, whereas the Soviet Union has not at this writing successfully used such stages at all for its launch vehicles.

A renewed lunar program focusing on a base would have unique value as a continuing technological stimulus. The reasoning is as follows. Lunar missions are in all qualitative essentials *short interplanetary missions* involving escape trajectories, deep space tracking, landings on another body, and return to Earth. They can thus provide most of the technological challenge of planetary missions but are quicker, cheaper, and safer. (Consider the outcome of the Apollo 13 Service Module explosion had it occurred halfway to Mars.) A long-term lunar base program would provide an operational matrix into which new developments in space technology could profitably be fitted as they became available: reusable orbital transfer vehicles (OTV), closed ecology life support systems, nuclear reactors for both stationary and propulsion use, advanced space suits, and the like. Furthermore, lunar capabilities can rather easily be reoriented for use in Earth orbit if necessary, just as the Apollo system was modified to produce Skylab. Systems designed solely for low Earth orbit, however, do not necessarily have the same two-way versatility. Deep-space capability implies Earth-orbit capability; the reverse is not true.

There is increasing concern that the United States may be losing its position as the preeminent space-faring nation. The Soviet challenge in space is still the most pressing one. A lunar base would have little military application, and, in fact, could provide a natural area for Soviet-American cooperation, but the technological stimulus it would provide should help prevent another "Sputnik surprise," which is never to be forgotten by anyone who lived through it.

Evaluation and Use of Lunar Resources

The only natural resource available in interplanetary space is energy, but all solid bodies offer materials as well. The Moon is the most convenient source of extraterrestrial materials, either for use on the Moon or in near-Earth space, with the possible exception of Earth-crossing asteroids. The use of lunar hydrogen and oxygen for rocket fuel was studied extensively during the 1960s (Lowman, 1966b), but the absence of indigenous water in all lunar rocks and soils so far sampled has discouraged this prospect. On the other hand, we now know that there are essentially inexhaustible amounts of aluminum, iron, silicon, titanium, magnesium, and oxygen (Phinney *et al.*, 1977), and the possibility of lunar hydrogen (as water or otherwise) has by no means been ruled out (Arnold, 1984). Furthermore, lunar materials, electromagnetically launched from the surface, are more competitive than they might appear because the launch energy per unit mass (*i.e.*, the

kinetic energy) depends on the *square* of the escape velocity. To place a given mass of material in near-Earth space from the surface of the Earth would thus take very roughly 22 times as much energy as it would from the Moon. For this reason, there has been a strong revival of interest in lunar raw materials for construction or shielding of large structures in Earth orbit. A satellite solar power system, for example, will probably only be economically feasible with the use of lunar materials (Glaser, 1974; O'Neill, 1975). The most valuable lunar resource would be hydrogen, which would greatly facilitate the establishment of an autonomous permanent colony, and perhaps a lunar refueling facility for chemical or nuclear rockets.

A lunar base will be an essential step toward establishing the nature and value of the Moon's resources by permitting long-range surface traverses, extensive sampling, and *in situ* analysis of data and samples. There is now no doubt that the Moon has useful resources; the questions are exactly what and where they are and how they can be utilized.

Establishment of a U.S. Presence

The exploration of the Moon has been frequently compared with that of Antarctica, a valid comparison with political implications. Both areas are nominally protected by treaties against national appropriation. However, it is generally recognized that a major reason for maintaining Antarctic bases is to lend substance to the Antarctic Treaty by presenting a national presence on the continent, preventing territorial claims from being established by default. Joyner and Schmitt (1984) have proposed a governing body similar to INTELSAT for lunar development, but pending such an arrangement, a lunar base would be valuable to maintain an American or international presence on the Moon.

Long-range Uses of the Moon

Two completely independent findings in recent years point to the probability that the physical universe is more hostile to intelligent life than had previously been believed. First is the very strong evidence that some and perhaps many of the great biological extinctions on Earth have been caused by catastrophic impacts (Alvarez *et al.*, 1980). The interval between such impacts may be only a few tens of millions of years, and if they are non-periodic, most life on Earth could be destroyed at any time, as has happened many times in geological history. The second finding is a negative one: radio astronomers to date have detected no intelligent signals from elsewhere in the universe, and there is no believable evidence that extraterrestrials have ever visited the Earth. It has been argued by Tipler (1980) that because interstellar colonization by von Neumann machines or otherwise is possible, and would be rapid in terms of cosmic time, the absence of extraterrestrials (or their machines) in the solar system means that there are none anywhere. Tipler suggests that we may be the only intelligences in the universe.

An obvious way of explaining the apparent absence of other intelligent life (assuming there to be some) is that the communicative lifetime may be reduced, perhaps to zero, by natural and uncontrollable catastrophes such as asteroidal impacts, supernovae, externally initiated glaciations, or the like. In other words, intelligent life in any given system may not last very long, in terms of geologic time, if it even arises at all.

The point of this discussion has been made many times before, as by Bernal (1939), for example: "If human society, or whatever emerges from it, is to escape complete destruction by inevitable geological or cosmological cataclysms, some means of escape from the Earth must be found. The development of space navigation, however fanciful it may seem at present, is a necessary one for human survival. . ." The Moon furnishes a uniquely convenient first step for the "escape" called for, to say nothing of providing material for a completely space-borne civilization of the kind visualized by O'Neill (1975). In the most basic terms, then, a lunar base could be the beginning of a long-range program to ensure the survival of the species.

RECOMMENDED MEASURES FOR A REVIVED LUNAR PROGRAM

There are several immediate technical measures that could be undertaken without major funding commitments to lay the groundwork for a lunar base program. The most obvious of these, described in the SSEC (1983) report, is the Lunar Geoscience Orbiter. This spacecraft would carry out a comprehensive program of remote sensing from lunar polar orbit intended to produce global composition maps as well as indirect data on the Moon's structure. Although not strictly necessary for establishment of a minimal lunar base, the LGO would be an important measure to rebuild American scientific capability for renewed lunar exploration. A concurrent measure with the same general objective would be continued or increased funding for study of Apollo samples and meteorites and for Earth-based astronomical studies of the Moon.

Another step that could be taken almost immediately would be to design modules for the proposed space station for eventual adaptation to use on the surface of the Moon, as mentioned earlier. Since most space station proponents agree that one of its functions should be to launch lunar and planetary missions, the proposal for dual use models should be reasonably welcome. Furthermore, it is consistent with the SSEC report's emphasis on "spacecraft inheritance and commonality of systems" as means of reducing costs.

A much more challenging step, but one with long-range implications, would be development of a reusable manned orbital transfer vehicle, possibly nuclear-powered. Solid-core fission rockets of the sort static-fired in the 1960s, using hydrogen as propellant, can produce specific impulses in the 800 second range (Glasstone, 1965), roughly twice the performance of hydrogen-oxygen engines. Gas-core fission rockets can in principle produce much higher I_{sp} figures (Hunter, 1965). However, the apparent scarcity of hydrogen on the Moon tends to lessen the advantage of nuclear rockets for Earth-Moon transportation, and it is possible that advanced chemical rockets will be more practical. At this point, one can say only that a permanently manned and periodically resupplied lunar base would provide ample justification for some sort of reusable orbital transfer vehicle. Such an OTV could, in principle, be adapted for planetary missions when desirable, widening the range of options for American space programs of the 21st Century.

SUMMARY AND CONCLUSIONS

Most of the reasons advanced for establishing a lunar base as the successor to the Apollo missions are still valid 12 years after the last of those missions. The Moon is still a scientifically interesting object in itself; it is a valuable site for observing the universe, and it represents usable territory with potentially valuable raw materials. Establishment and operation of a lunar base or complex of bases would be a unique and continuing stimulus to space technology, because the Moon is actually a conveniently close planet that can be reached in less time than it took the first scheduled airliner to cross the Pacific Ocean (a 5½ day trip by China Clipper in 1935). Lunar missions are thus in all essentials short interplanetary missions, unlike low Earth orbit operations, and development of an Earth-Moon transportation system would to a large degree produce a planetary capability as well.

When these predictable benefits are added to the feasibility of an initial lunar base, demonstrated by the six missions that began at Tranquillity Base, it is clear that the Moon is a leading contender for the focus of American space activities of the near future.

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EVOLUTION OF CONCEPTS FOR LUNAR BASES

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Man's aspiration to colonize the Moon has a very long history. In the second century, Lucian wrote of a trip to the Moon. In 1638, Wilkins mentioned lunar colonies after Kepler's early telescopic observations of the lunar surface. The literature continues almost uninterrupted with the imaginations of writers such as Cyrano de Bergerac and Jules Verne. Verne's fictional launch from Florida was a strange parallel to the Apollo program. Lunar base concepts include those of Rodney Johnson based on 1960s technology (from a May, 1969 *Science Journal* special issue featuring man on the Moon) and the associated Lunar Exploration Systems for Apollo (LESA) and Mission Modes and Systems Analysis (MIMOSA) studies. Might the strong drive of mankind to push outward and explore help mankind set a common goal? Could mankind unite in the future to bring about construction of a lunar base and exploration of the space beyond?

INTRODUCTION

This paper traces the evolution of lunar base concepts. The time span is at least 2000 years. The paper is divided into the following parts: early history to the 1870s (when Mars replaced the Moon as the foremost destination of cosmic voyagers), early 1900s through World War II, and the pre-Apollo and post-Apollo period.

Many old tales about trips to the Moon appear in the literature of most space-using nations. They provide a common bond that the creation of a lunar base would help focus. Effort involved in building such a base could be a beginning of the establishment of a shared culture. An innovative and properly planned initiative toward a lunar base could be a significant element in reducing international tensions (Johnson and Leonard, 1984). Through constructive interaction in the establishment of a lunar colony, nations may learn to work together in ways helpful in promoting world peace.

EARLY HISTORY

The earliest, but legendary, casualty of space was Icarus, the astronaut son of Daedalus, who flew too close to the sun. His wings of wax and feathers disintegrated, and he fell back into the sea.

In the second century A.D., a Syrian resident of Athens named Lucian gave an account of a lunar trip by fifty men aboard a ship in a book called *True History*. They were caught in an Atlantic storm that carried them toward the Moon (a large, circular illuminated

island) where, after seven days of travel, they landed. They became involved in a war between creatures of the Moon and those from the Sun. After a truce in the war, Lucian sailed back to Earth for more adventures (Clarke, 1968).

One night in 1609 Galileo turned a telescope toward the Moon to make observations that showed the Moon not to be a smooth disk but rather a world of mountains and valleys. The impact of that discovery was soon noted in lunar base literature.

In the 17th Century, Johannes Kepler wrote fiction to disseminate his explanations of planetary motion. In *Somnium*, or *Astronomy of the Moon*, he avoided hypothesizing a transportation system. His travelers were carried to the Moon during sleep by spirits who crossed on a bridge of shadow during an eclipse. They found on the Moon creatures who spent their days in caves to avoid the sun's heat. Kepler emphasized the extremes of the lunar climate and the observed nature of its topography (Clarke, 1968).

Cyrano de Bergerac wrote *Voyages to the Moon and Sun* a few years after Kepler's *Somnium*. His hero was lifted with the morning dew in one form of launch. Another approach was to coat the body with beef marrow, which the waning Moon attracted. He also used solar energy to power jet propulsion, and in one instance tossed a magnetized ball upward so that his metal ship was pulled along. Francis Godwin, in his 1638 book, had as a hero an individual who traveled by goose-power. This Godwin character was encountered on the Moon in Cyrano de Bergerac's book.

The first discussion in print about a lunar colony is attributed to Bishop John Wilkins. In his 1638 book, *A Discourse Concerning a New World and Another Planet*, he voiced the opinions that man would one day learn to fly and would plant a colony on the Moon.

In 1783 two Frenchmen flew over Paris in a balloon and caused space flight to appear attainable. However, hopes were dashed as men encountered the difficulties of high altitude balloon flight; several would-be astronauts died from lack of oxygen. Man had begun to learn that the road to the Moon must be through the vacuum of space.

It was not until 1827 that a story stressed that the ship "must cross an airless void in bitter cold." *A Voyage to the Moon*, by Joseph Atterley (George Tucker) is also notable in that it is the first American entry, that its spacecraft was the first to be coated with an anti-gravity material, and that it includes scientific data for its own sake (Barron, 1981).

Jules Verne wrote *From the Earth to the Moon* in 1865. Verne combined science, speculation, and imagination in a tale of a launch from Florida with 400,000 pounds of guncotton in a 900-foot cannon. The escape velocity attained was 25,000 miles per hour, and air friction caused the vehicle to heat in the atmosphere; subsequently it was steered by rockets, and weightlessness was encountered in space.

THROUGH WORLD WAR II

Soon after 1900, H.G. Wells wrote *Men in the Moon*. His book contains elements of science fiction (*e.g.*, negative gravity and lunar inhabitants called Selenites). In Russia, Konstantin Tsiolkovsky, a serious space travel exponent, had dreams of spaceflight that he developed in many technical articles and in the novel *Outside the Earth*.

Literature relating to lunar exploration, as it is adjusted to increased technical knowledge, is found in the *Journal of the British Interplanetary Society*, which was first founded in 1933 and then revived after World War II ended. In the United States, Willy Ley conducted a space flight symposium at New York's Hayden Planetarium on October 12, 1951. This event led to a famous set of *Collier's* magazine articles by Werner von Braun that popularized the idea of a future in space.

After World War II, the lunar base literature began to focus on the technical requirements, the critical issues to be resolved, and the associated technology. Rocketry had come of age at Peenemünde. It became clear that even larger rockets with the capability of providing transportation to the Moon could be developed. The trend was away from the fanciful to the more technologically reasonable (but sometimes extreme) solutions to the challenge of establishing a lunar base.

A book first published in 1949 (Bonestell and Ley, 1958) described a trip to the Moon by a winged single-stage rocket ship with an atomic rocket motor. A single layer of shielding separated the crew's cabin in the nose from the rest of the ship. The ship on the ground was surrounded by concrete shielding open at the top. Takeoff was from a desolate location on a mountain top near the equator, above the densest layers of the Earth's atmosphere, with acceleration at 4 g for about 500 seconds. The crew encountered a difficult 4-day trip in weightlessness with very little to do. The pilot was relegated to monitoring instruments for the lunar landing, while preset controls did the work. Bonestell painted a concept of the beginnings of a lunar base adjacent to the winged rocket that provided weekly transport to Earth.

APPROACHES TO BUILDING LUNAR SHELTERS

Szilard (1959) noted that the building of a lunar base might occur in five to ten years. This article emphasized that the structural design of the base would be influenced by its purpose, the lunar conditions, and the construction materials used. The recommended lunar base structure was a completely prefabricated sphere supported by four or more adjustable legs attached to a circular edge beam. A crew of five could be accommodated in a closed biological circuit including plants. Beryllium alloys and annealed aluminosilicate glasses provided structural integrity and transparency. Shielding was provided by coolants circulated between inner and outer walls of the sphere.

Holbrook (1958) likened the establishment of a lunar base to a combination Normandy Invasion and Mt. Everest Expedition. Many ideas have been offered for the design of shelters for a lunar base. One suggestion was inflated shells rigidized by a plastic hardening compound (Helvey, 1960), with lunar soil radiation shielding and micrometeoroid bumpers installed over them. To accommodate the deep dust anticipated by some scientists, Rinehart (1959) proposed a cylinder that would lie on its side floating half-submerged in dust.

DiLeonardo (1962) investigated transporting structural tension members from Earth because they are relatively light, and mixing alkali transported from Earth with pumiceous lunar dust to make glass to be used for compression members. An alternative was to quarry lunar rock for use in shelter construction. The Army Lunar Construction and Mapping

Program (1960) proposed cylinders for shelter to be laid end-to-end in a trench under several feet of lunar soil. Blasting might be used to assist excavation, but placement and backfill would be accomplished by a multi-purpose construction vehicle.

DeNike and Zahn (1962) suggested tunneling and then lining the tunnel to retain pressurization. DiLeonardo (1962) proposed impacting a projectile on the Moon that would penetrate to a predetermined depth where an explosive charge would detonate to form a cavity. The cavity, when excavated and lined, would provide shelter. Reedy (1961) used existing crevasses or caverns for protection from the lunar environment. Johnson (1964) investigated criteria for the design of structures to be erected at a permanent lunar base with particular attention to effects of the lower (1/6 terrestrial) gravitational field.

PRE-APOLLO AND POST-APOLLO UNTIL THE PRESENT

The early 1960s was a time of intense study of lunar base concepts. The Apollo program was being pursued with enthusiasm and vigor. Planners sought to find a way to transition with Apollo technology from short-term manned visits to the Moon, to extended visits associated with semi-permanent lunar bases and colonies. Figure 1 shows one

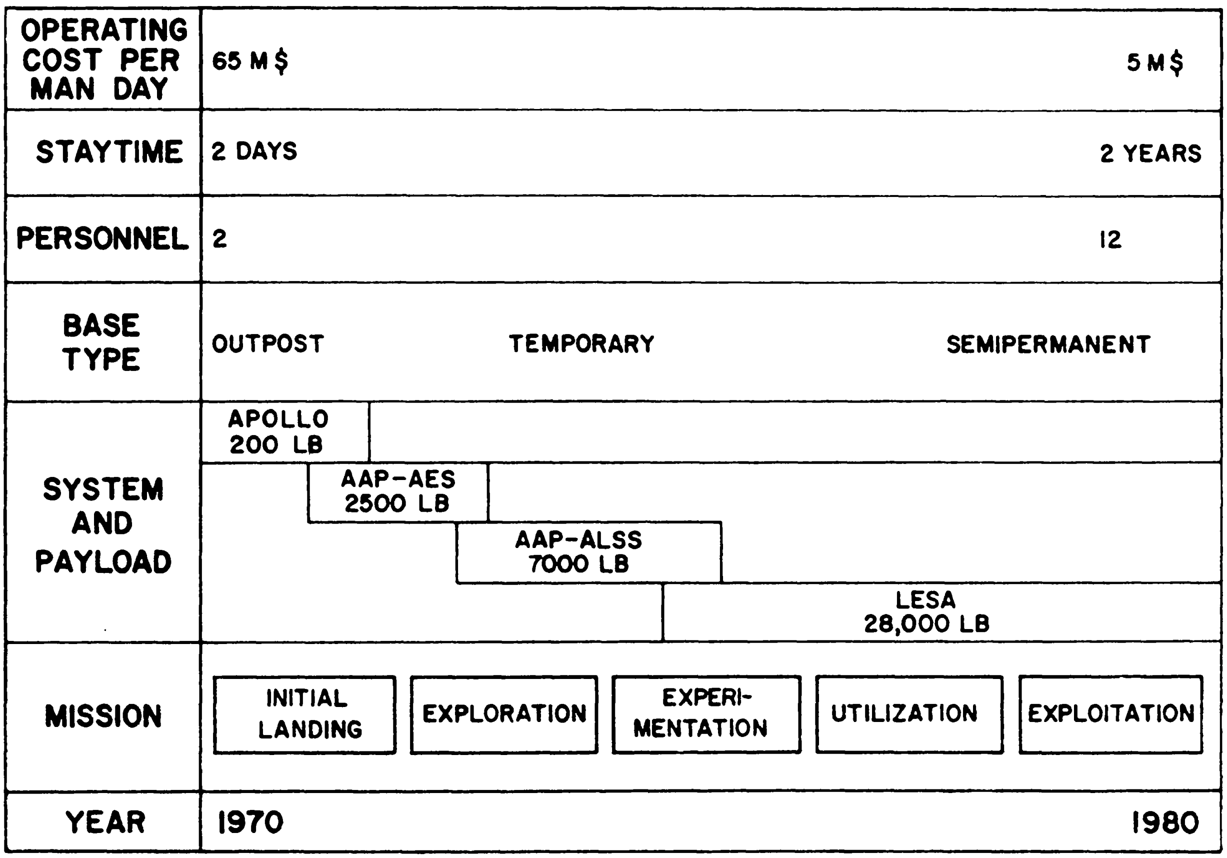

Figure 1. Projected evolutionary trends in lunar base development. Based on an orderly process of upgrading facilities, obtaining longer stay-times, and reducing operating costs. See Table 1 for acronyms (Johnson, 1966, page 368).

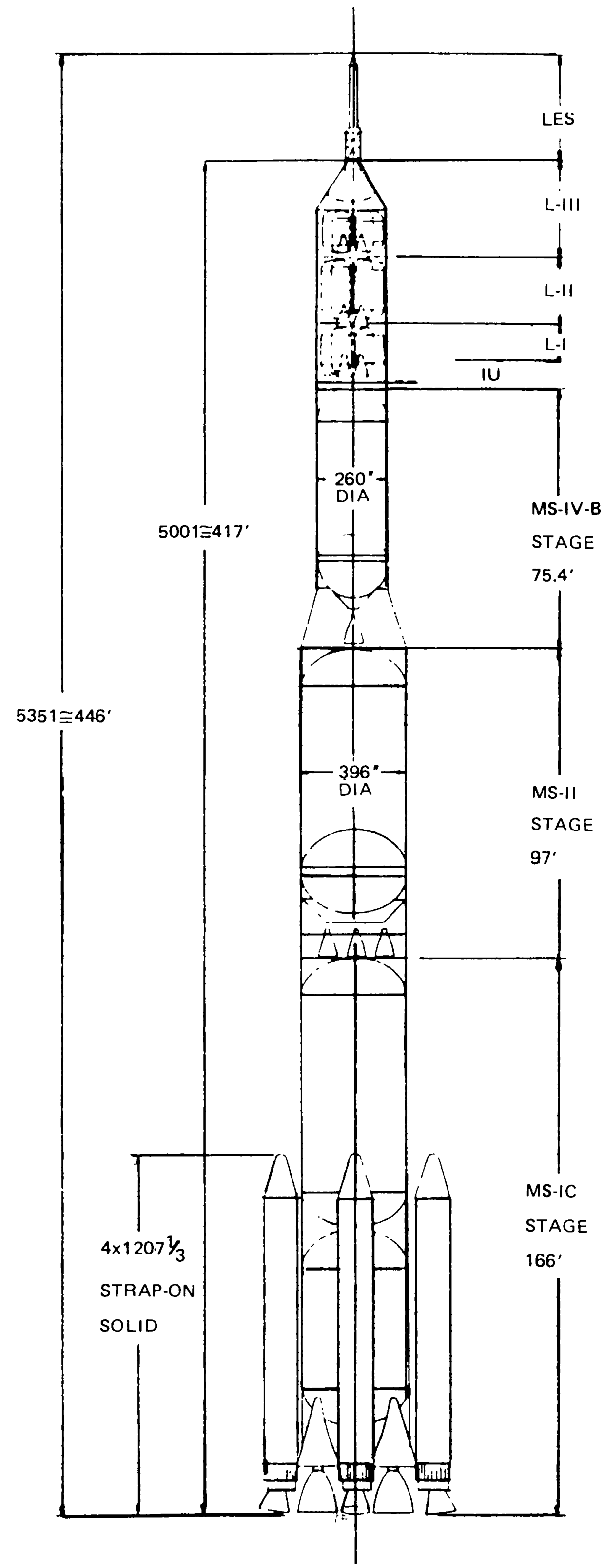

Figure 2. Extended Launch Vehicle (ELV) for six-man direct manned lunar landing. First stage five F-1 engines with 1.522 million pounds thrust each at liftoff plus four 120-inch 7-segment rocket motors. Overall system envisioned as having translunar payload capability of about 85,000 kg (unpublished NASA Report of 1966).

Figure 3. LESA Base Model 2 for accommodating six men for six months on the Moon. Involved is about 46,000 pounds of payload on the Moon, including a 10-kilowatt nuclear power unit, a 3765-lb. roving vehicle with an extended mobility module, and equipment to place lunar soil shielding (Boeing, 1963b).

example of the development flow that was considered feasible based on a systematic upgrading of the Saturn V transportation system to 111 percent and then 188 percent of basic. Figure 2 shows a view of an advanced Saturn V with strap-on solid rockets and a multi-stage stack extending to a height of approximately 446 feet. Some acronyms of the lunar basing investigations of the 1960s are presented in Table 1.

Figure 3 from the LESA Initial Concept (Boeing, 1963b) shows an artists' rendition of Base Model 2 on the surface of the Moon. This model envisioned six men on the Moon for six months. The LRV would have the capability for 3000 miles travel. LESA contemplated a building block approach based on several different modules. Two feet of soil for shielding is shown over the top and within expandable caissons on the sides of the shelter. A later study (Lockheed, 1965) portrayed the soil emplacement sequence (Fig. 4). Base Model 2 was considered a favorable approach following Apollo landings (Johnson, 1966). It would have required eight Saturn V launches per year to furnish 72 man-months per year on the lunar surface. Anticipated were one reconnaissance trip,

Table 1. Acronyms for Proposed Lunar Basing Options for Apollo

Program	Full Title
AAP-AES	Apollo Applications Program - Apollo Extension Systems
AAP-ALSS	Apollo Applications Program - Apollo Logistics Support System
LESA	Lunar Exploration System for Apollo
MIMOSA	Study of Mission Modes and System Analysis for Lunar Exploration
MOBEV	Lunar Surface Mobility Systems Comparison and Evolution Study
MOLAB	A concept for a long-range mobile laboratory that was associated with ALSS

one manning trip (assuming six men per vehicle), two rotation trips, and four logistics payloads. In contrast, the LESA Base Model 4 would have required 18 Saturn V launches per year and yielded 216 man-months per year.

Prime power for Base 2 was to come from a nuclear thermoelectric powerplant concept with a rating of 10 kilowatts. Standby power was envisioned to be furnished

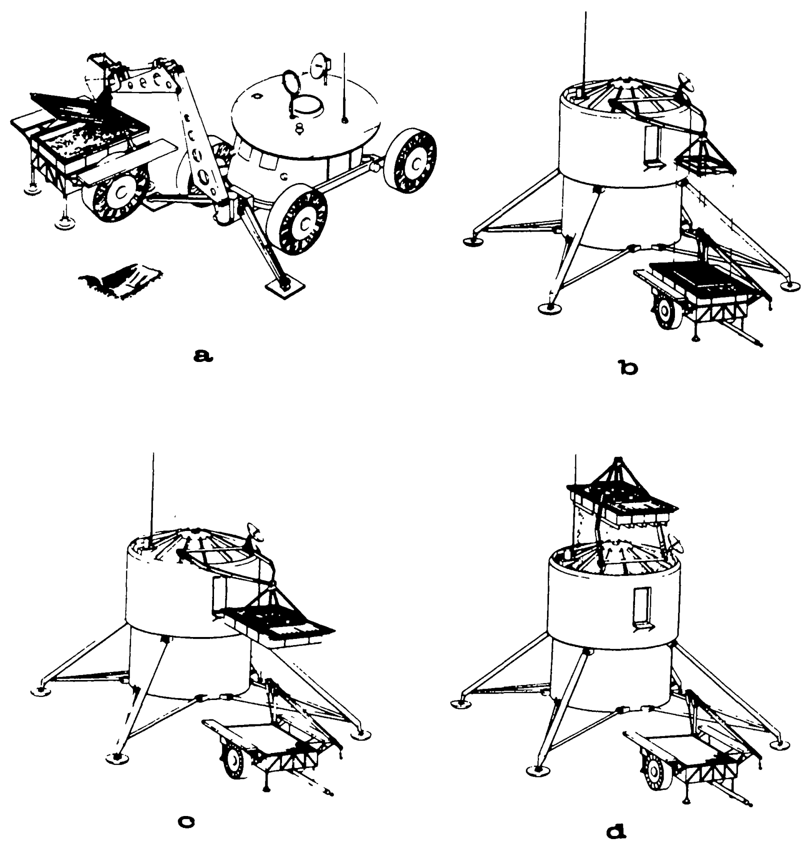

Figure 4. Soil operations sequence for shielding placement. (a) Soil excavation by backhoe. Soil box pulled by LRV trailer for soil transportation. (b) and (c) A-frame with hoist to lift box. (d) Release of soil (Lockheed, 1965).

by a fuel cell with a 15-kilowatt average load power rating. Larger bases (LESA 3 and 4) were to be served by a 100-kilowatt nuclear (Rankine cycle) SNAP 8 reactor. Nuclear reactor power plants were to be remotely placed and shielded with lunar material (Boeing, 1963a).

In 1969 the lunar colony concept (Fig. 5) was developed to encompass a lunar base buried under lunar soil (Johnson, 1969). The sequence of events thought to be possible was a landing in 1969, resources development in 1973–75, a scientific station in 1975, and the lunar colony by 1978.

Lockheed (1967) outlined three exploration programs, each emphasizing science accomplishments. Program III was to establish four temporary lunar bases, including two at Grimaldi Crater, one at the center of the farside, and another at the south pole. At Grimaldi, a base of two years duration was to perform astronomy, biology, and applied

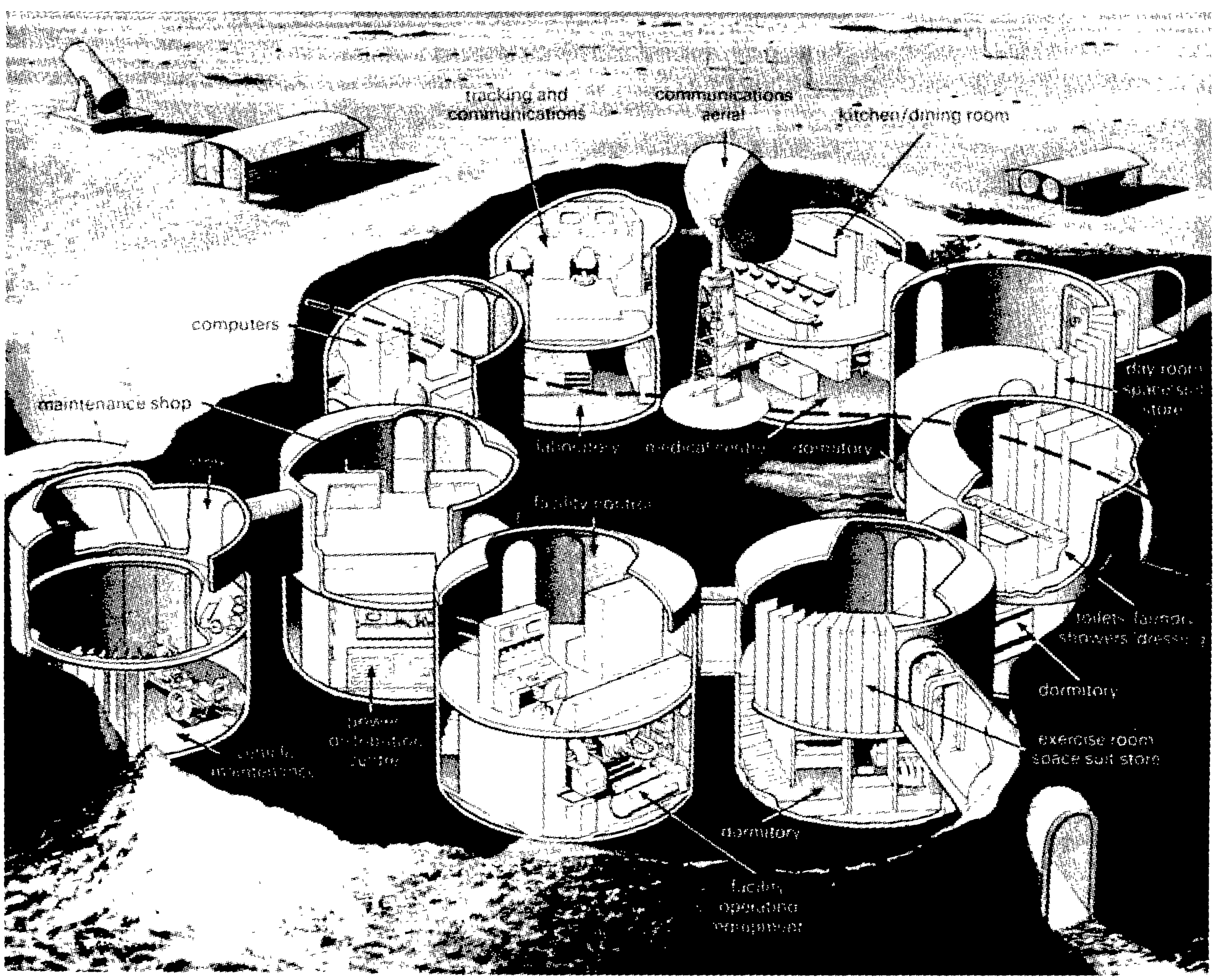

Figure 5. Projected lunar colony including nuclear power plant at 760-m safety radius, future housing, hydroponic algae farm, sewage treatment, photosynthesis, housing and command structure, telescope, cryogenic storage, launch pads, guidance antennae, and communications (Johnson, 1969).

science experiments. The program would have required 63 Saturn V launches between 1971 and 1988.

Recent studies by Duke *et al.* (1984), Staehle (1983), and Carroll *et al.* (1983) emphasize the exploitation of materials found on the Moon. Usage of lunar materials such as oxygen is sought to offset high Earth-to-orbit transportation costs.

CONCLUSION

Science fiction was not only the domain of the scientist turned writer but also of the poet, as evidenced by the poet Alfred, Lord Tennyson, who expressed his view of the future world in "Locksley Hall:"

For I dipt into the future, far as human eye could see,
Saw the Vision of the world and all the wonder that would be;
Saw the heavens fill with commerce, argosies of magic sails,
Pilots of the purple twilight, dropping down with costly bales.

It is possible that in the future we will see spacecraft returning to space stations in Earth orbit with "costly bales" from bases on the Moon. Man has developed the capability of colonizing the Moon. Whether he will do so, and for what reasons and when, remain unanswered questions.

Today we live in a tremendously fragmented world. As Margaret Mead observed, mankind needs a mutually shared body of materials, events and efforts that gives everyone, whether from a technologically advanced society or a primitive one, a basis for communication and understanding (Mead, 1965). To date the unifying force is weak. The conquest of space, of which a lunar colony or observatory is but a small first step, could be the beginning of the development of important elements of a shared culture. Much of mythology deals with humanity's battle with nature. Science fiction deals with man's use of technology in this effort. Creation of a lunar base would be but one more step by man to bring to reality positive elements of mythology and science fiction. Perhaps the establishment of a lunar base could be an element in the dawning of a bright new age for mankind—the age of space exploration.

Acknowledgments. *Stewart Johnson and Ray Leonard acknowledge the support of The BDM Corporation and The Zia Company in the preparation of this paper.*

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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 telescopic 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

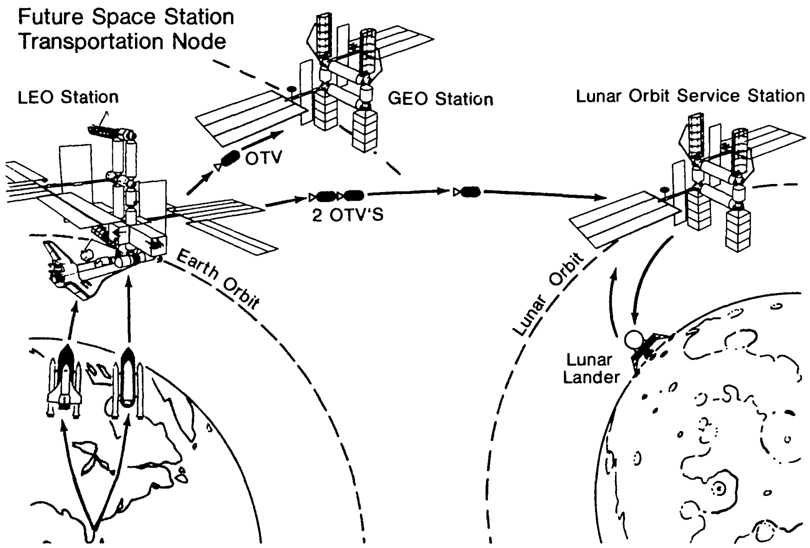

Figure 1. The Space Transportation System of the future may service a station in geosynchronous orbit as well as a lunar base via a station in lunar space. The lift capacity of the Shuttle fleet may be augmented by an unmanned heavy lift vehicle, designed to ship fuel and consumables to space.

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

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

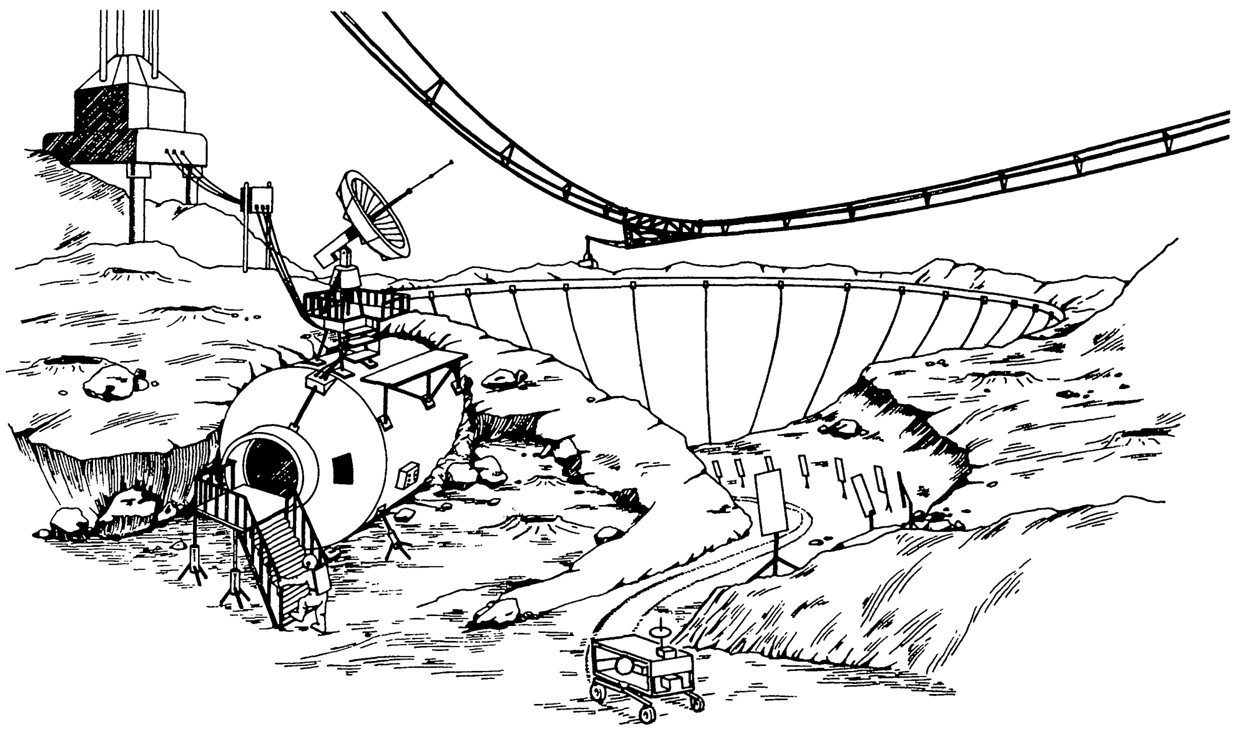

Figure 2. A radio telescope located on the farside of the Moon would be shielded from background noise generated by terrestrial sources. Although depicted here as a parabolic dish in a convenient crater, an initial lunar instrument may well be a phased array of dipole antennas.

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

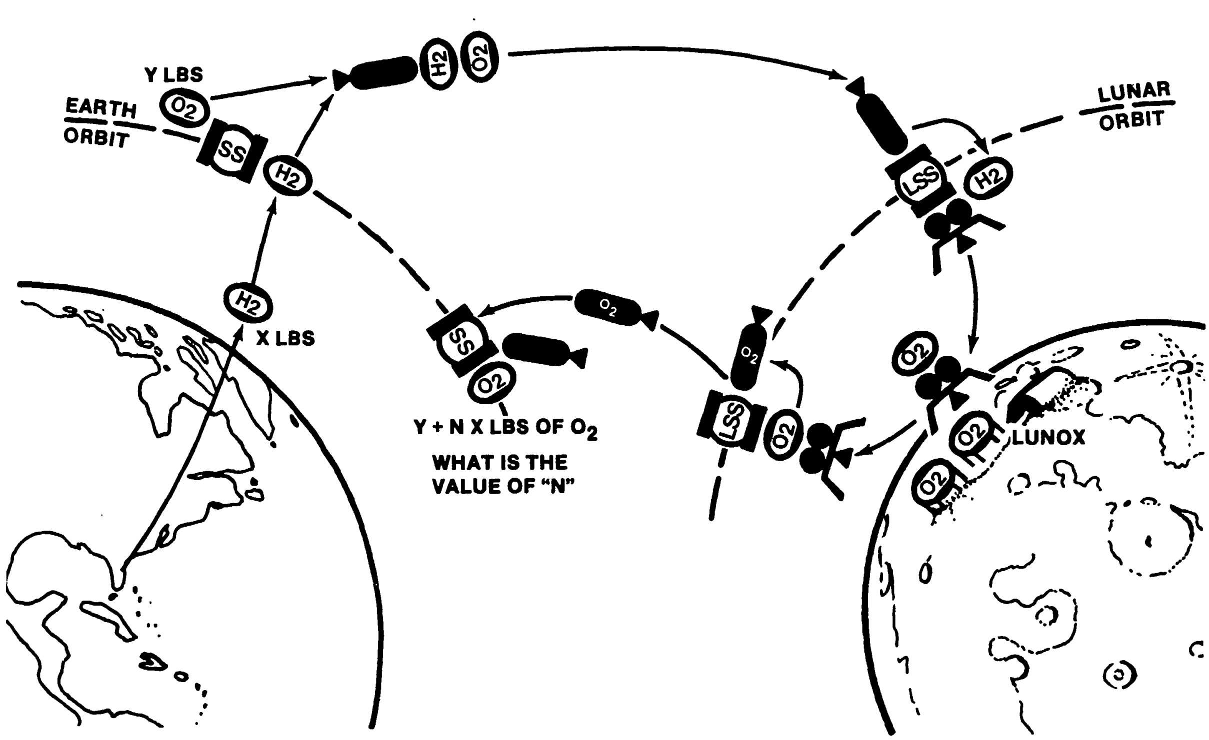

Figure 3. Liquid oxygen fuel (LOX), manufactured on the Moon and delivered to low-Earth orbit may become a profitable export for a lunar base. A critical parameter in analyses of the system is the mass payback ratio, defined as the ratio of the excess lunar LOX in LEO to the liquid hydrogen fuel delivered from Earth to LEO.

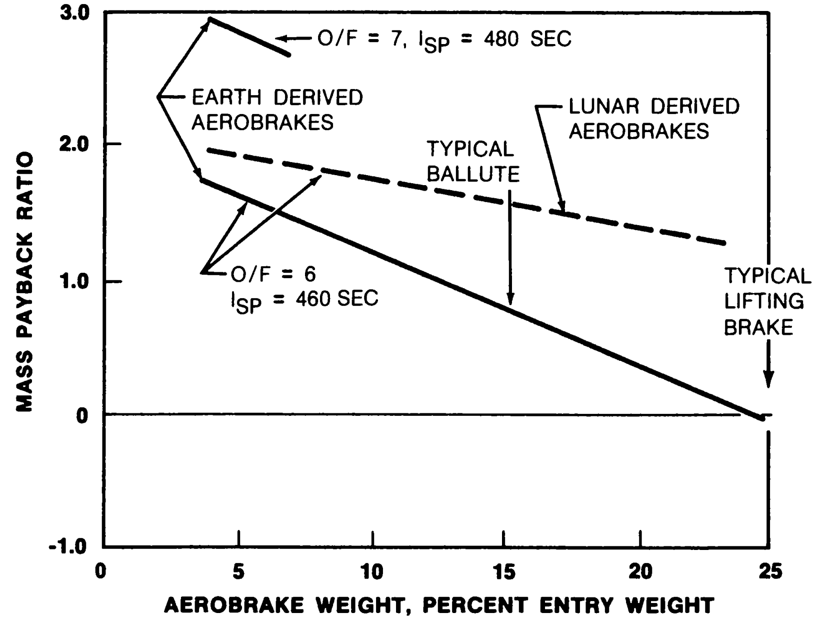

Figure 4. The mass payback ratio for lunar LOX delivered to LEO is sensitive to the design characteristics of the OTV used as a lunar freighter. The fractional mass of the OTV aerobrake and the oxidizer to fuel ratio are key parameters. Manufacture of aerobrakes on the Moon would enhance system performance.

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

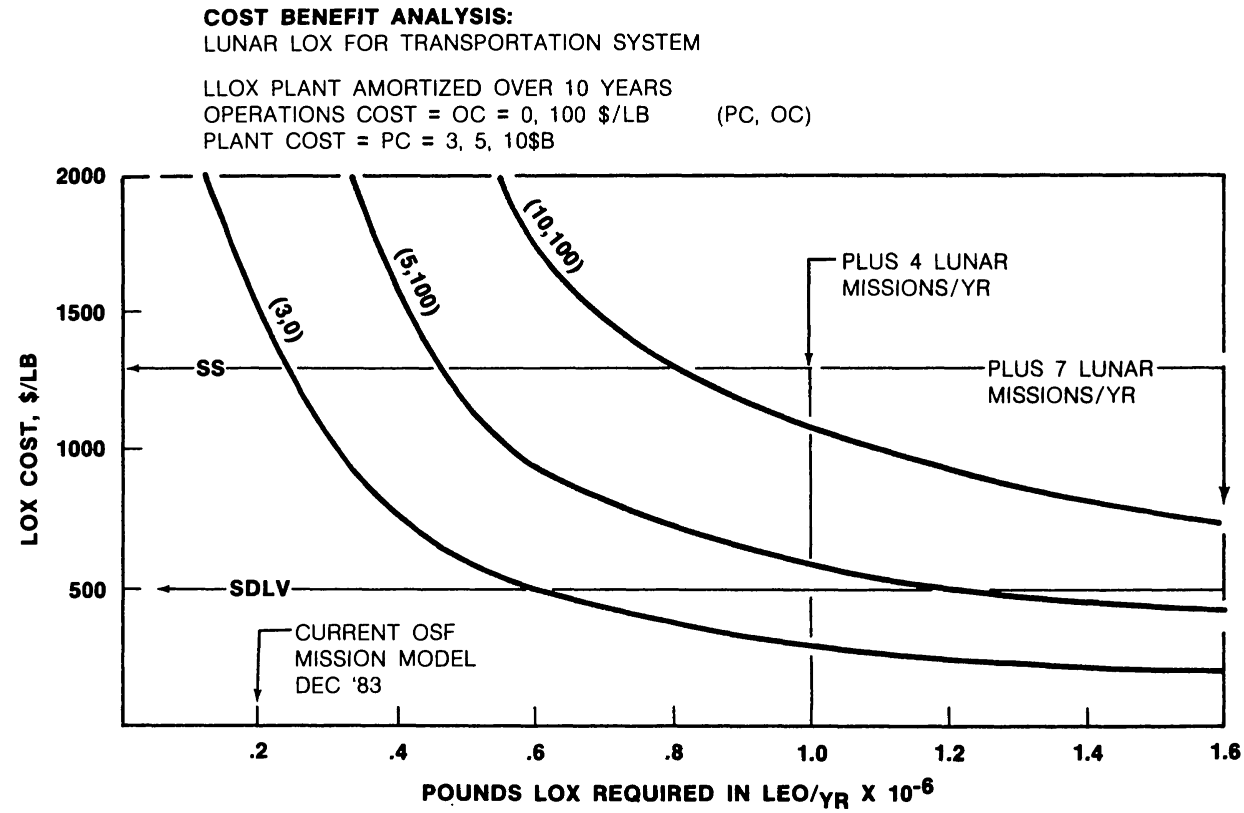

Figure 5. A simple cost-benefit analysis assumes that a lunar oxygen production facility has its capital costs amortized solely by "profits" on delivery of LOX to LEO. While lunar oxygen is competitive with shuttle delivery in all cases, introduction of a cost-efficient heavy lift vehicle reduces the advantage under more conservative cost estimates for the lunar operation. If costs of lunar LOX are shared with other activities, the advantage is restored.

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

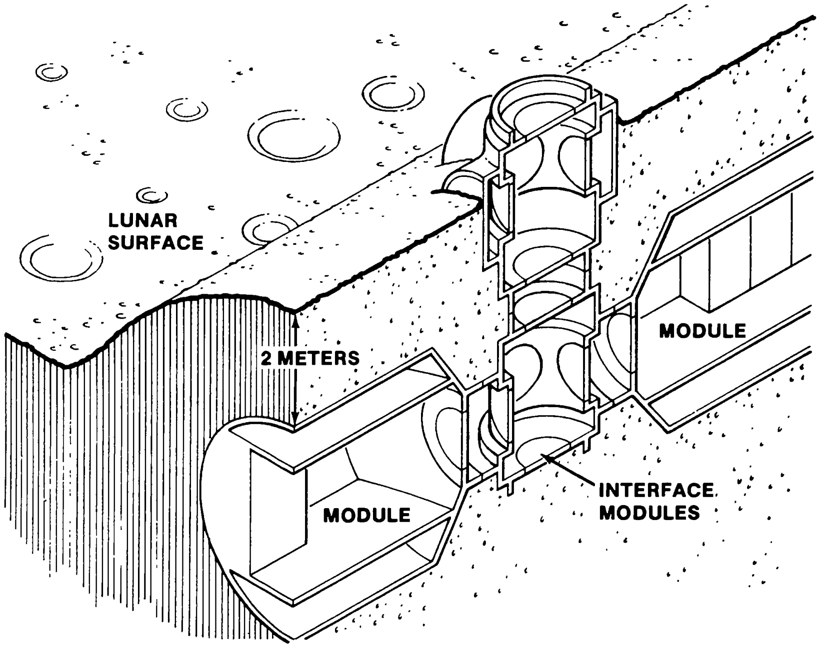

Figure 6. The first lunar base habitats and laboratories could be space station modules, buried in the lunar regolith for protection from solar flare radiation. Interface modules not only interconnect the buried structures but also can be stacked to create exits to the surface.

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

Table 1. Lunar Base Growth Phases: Science Base Scenario

A growing capability to do lunar science and to use the Moon as a research base for other disciplines, using lunar resources to a limited extent to support operations.

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

Phase II: Research outpost
- Minimum base, temporarily occupied, totally resupplied from Earth
- Small telescope/Geoscience module
- Short range science sorties
- Instrument package emplacement

Phase III: Operational base
- Permanently occupied facility
- Consumable production/Recycling pilot plant
- Longer range science sorties
- Geoscience/Biomedical laboratory
- Experimental lunar radiotelescope
- Extended surface science experiment packages

Phase IV: Advanced base
- Advanced consumable production
- Satellite outposts
- Advanced geoscience laboratory
- Plant research laboratory
- Advanced astronomical observatory
- Long-range surface exploration

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.

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.

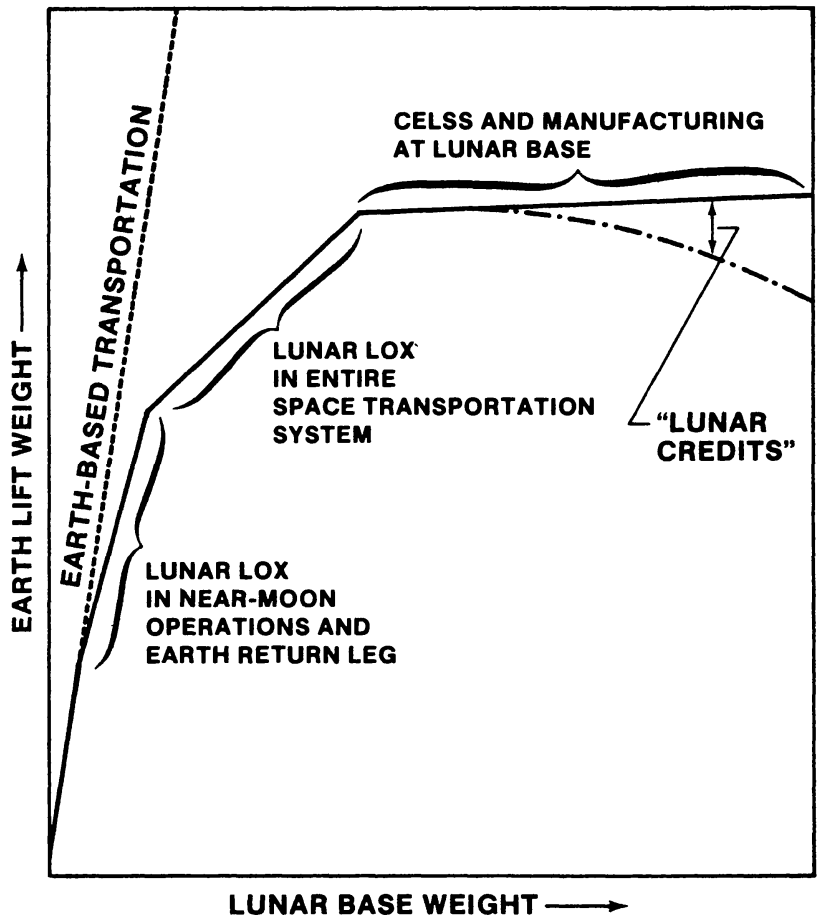

Figure 7. Initially, almost 7 kg must be lifted into LEO for every kg landed on the Moon. As lunar oxygen is introduced into the transportation system, the ratio improves as a unit mass goes from Earth to Moon with only little overhead in the system. In a Phase IV advanced base, the growth of lunar surface infrastructure becomes only weakly dependent on imports from Earth. A favorable balance of trade is ultimately conceivable.

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.

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.

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PRELIMINARY DESIGN OF A PERMANENTLY MANNED LUNAR SURFACE RESEARCH BASE

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A brief study has been performed to assess the advantages and/or disadvantages of a lunar surface space base for civilian research and development. The suitability of undertaking scientific investigations in the diverse fields of astronomy, high-energy physics, selenology, planetary exploration, Earth sciences, and life sciences was considered. A lunar base was conceived to conduct the identified science, along with transportation requirements to establish and support continued operations at the base. A rough order of magnitude (ROM) estimate of the cost to deploy and operate the lunar base for a period of three years was made. Starting with the space station will assure performance of important low-Earth-orbit science and would also set in place certain elements of the transportation infrastructure found necessary to deploy and sustain a lunar base at a reasonable cost level. It is suggested that a lunar base be given serious consideration as a longer term goal of space policy, capable of providing important direction to the space station initiative.

INTRODUCTION

The purpose of this study is to define a concept for a permanently manned research base on the lunar surface and a manned reconnaissance mission that would precede base construction. A key study assumption limits the technology used for these two missions to that which is currently available, such as the space shuttle and spacelab, or to technology that will be available in the near term, such as space station and aerobraking. The remainder of this paper highlights the details of the two missions along with the science experiments to be carried out during each phase. The transportation network needed to accomplish these missions is also presented. A more complete discussion of these topics can be found in the references cited at the end of this paper.

TRANSPORTATION SYSTEM

Three major components of a transportation network were assumed to be in existence before the reconnaissance mission began. These elements included the space shuttle, a low-Earth-orbit staging point (presumably the space station), and a high performance space-based OTV. Only the OTV element required further definition for the purposes of this study. The OTVs used here are configurations proposed by NASA/JSC (Lineberry, personal communication, 1983) for use in Earth-orbital applications and for high-energy interplanetary missions. Each OTV has a maximum 27,216 kg (60,000 lb) of usable propellant and an I_{sp} of 460 seconds (LH_2-LO_2). A thrust level of 147,000 N (33,000 lbf) was assumed, which is representative of two RL-10 engines. The gravity losses corresponding to the

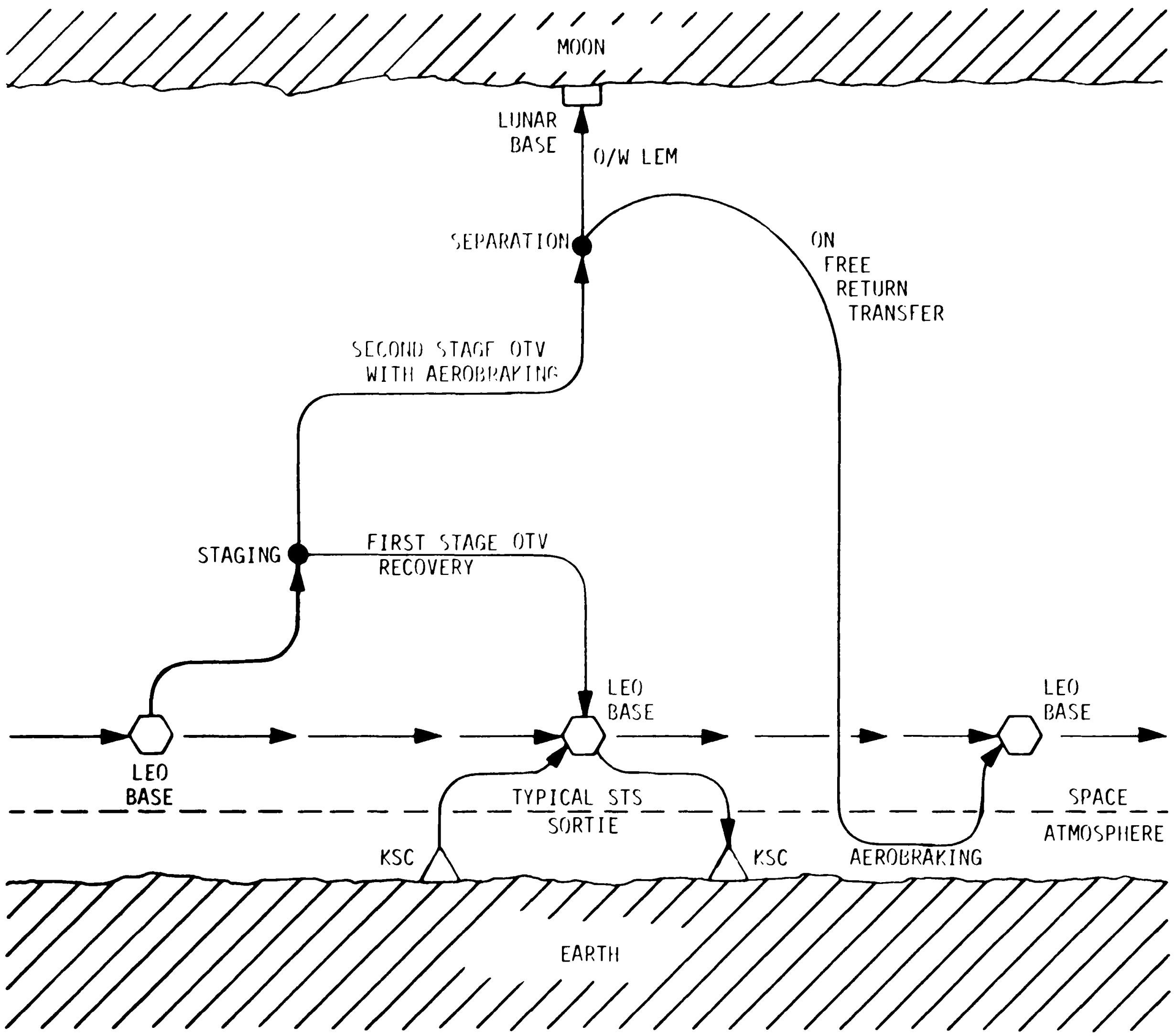

Figure 1. One way, unmanned cargo delivery mode.

resultant burn times are approximately 3%. As shown in Figs. 1 and 2, the first stage returns to LEO propulsively while the second stage returns using an aero-assisted maneuver. These two figures also show the two methods that would be used to deliver cargo and personnel to the Moon. For unmanned cargo sorties, a mission-unique, expendable lander is placed on an intercept course for the Moon and lands on the surface using its own propulsion system. After separation from the lander, the second stage of the OTV is retargeted for a free return to near-Earth space. For manned missions, the second stage will rendezvous in low lunar orbit with a prepositioned lunar excursion module (LEM) where the crew and LEM propellant will be transferred for descent to the surface. Crew retrieval will be accomplished by reversing this procedure.

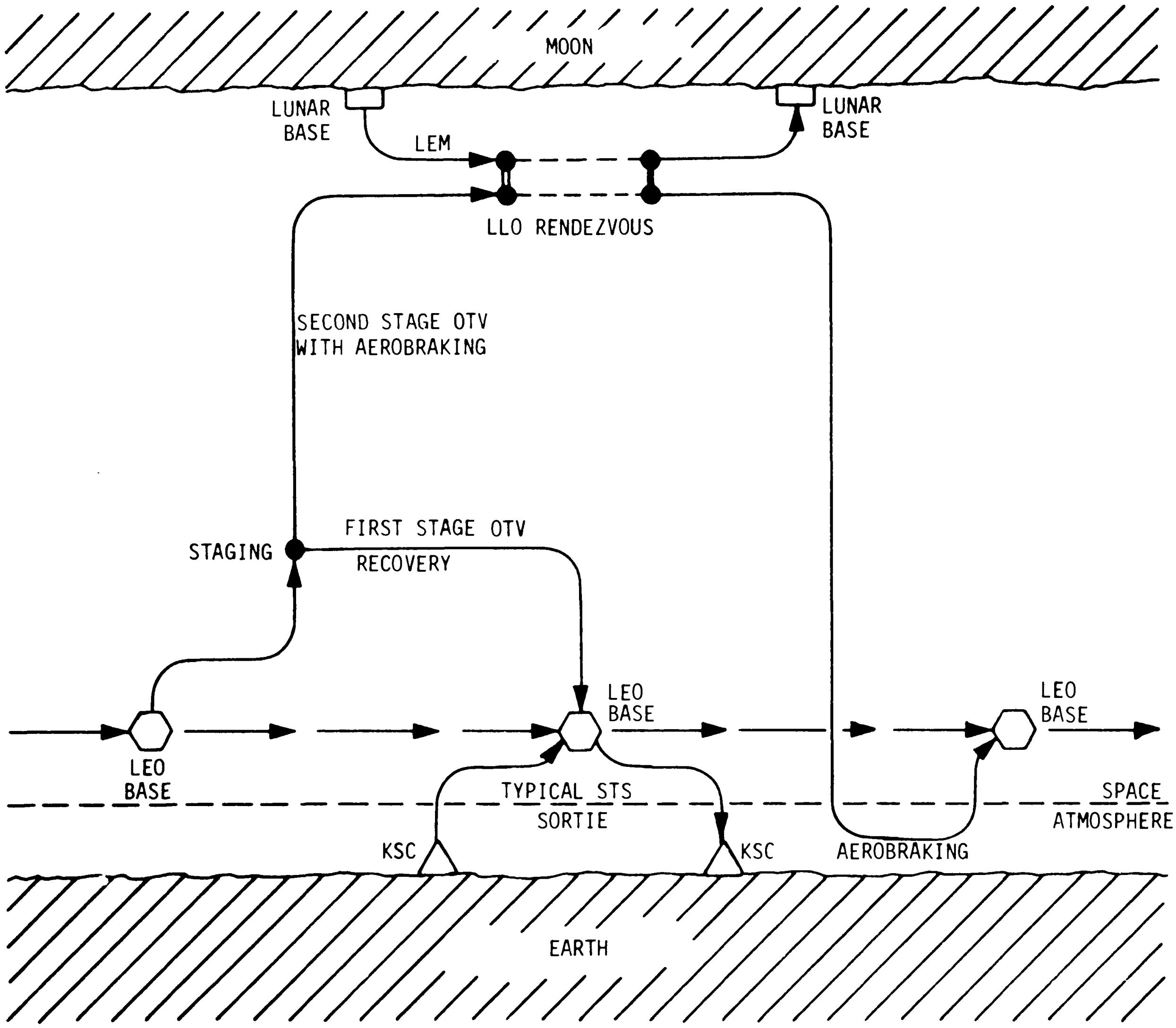

Figure 2. Manned sortie mode.

SITE RECONNAISSANCE AND SELECTION

An exploration team consisting of four individuals would spend up to 30 days exploring a region 50 km in radius that has been previously selected from remotely obtained data. Two surface vehicles would be used with two crew members per vehicle to carry out the exploration (Science Applications International Corp., 1984a). For safety reasons these vehicles would operate in tandem rather than individually. The two surface exploration vehicles would each consist of a rover and a trailer, the latter containing crew quarters and experiment facilities. The rovers would have the capability to move moderate amounts of lunar soil in order to expose subsurface strata. With the exception of the science

experiments, both rovers and trailers would be identical and capable of supporting the entire crew under emergency conditions. A mass budget of 2400 kg has been assumed for the instruments needed to ascertain which site is best suited for the base. These instruments would focus on the local composition, seismic characteristics, and stratigraphic make-up of each candidate site. Preliminary data analysis would be conducted on board the two trailers with more detailed analyses to be carried out upon return to Earth. These analyses would support the final site selection for the permanent base.

This segment of the base deployment mission is anticipated to require 60–90 days from first shuttle launch to crew recovery and would require a total of 12 shuttle launches. The shuttle launches would lift the two rover/trailer combinations, their lander, the LEM, and all necessary propellant into low-Earth orbit. Four sorties by the two-stage OTV would then be needed to complete the reconnaissance. The first two sorties would deploy the rovers and trailers to the surface and place the unfueled LEM in low orbit. The remaining two sorties would be used to deliver and subsequently recover the surface team. The LEM and all surface equipment would remain for use by the research base personnel.

OPERATIONAL BASE

Figure 3 shows the proposed configuration for the initial operational base (Science Applications International Corp., 1984b). Each of the three main modules would be buried

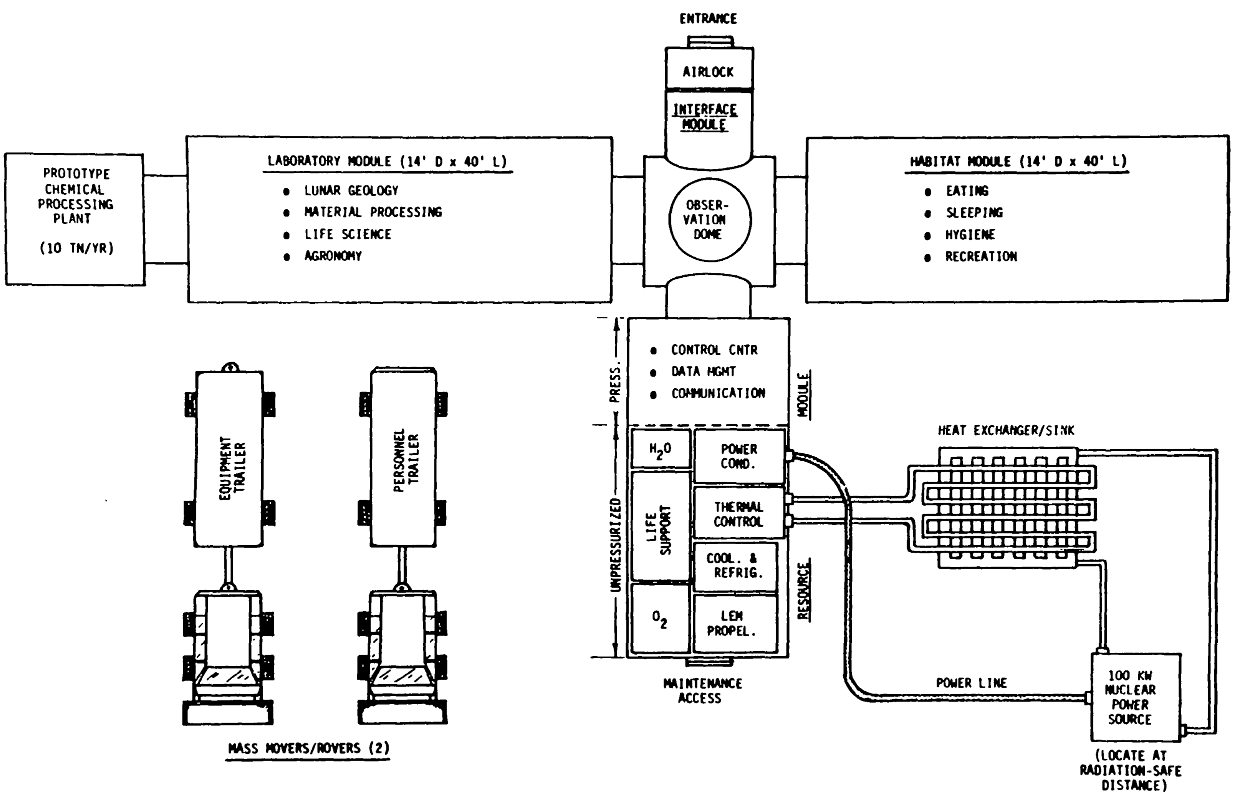

Figure 3. Initial base concept (7-person crew).

to provide both thermal and radiation protection for the crew. The rovers left by the reconnaissance crew would be used to position these modules and cover them with soil. The three main modules are connected by the airlock/interface module and are supplied with power from a 100-kW nuclear power source. This power system has been oversized for the base configuration shown here but provides for future growth of the facility. Table 1 shows a possible strategy for the deployment and initial operation of this base.

A seven-member crew, consisting of six scientist/technicians and a LEM pilot, would operate the base, each serving a four-month tour of duty. Half of the crew would be replaced every two months to maintain a core of experienced crewmembers at the station at all times. In addition, two unmanned logistical resupply missions would be flown each year to replace base consumables. This translates into an annual requirement of 18 shuttle flights and eight OTV sorties.

A diverse range of experimental investigations would be carried out at this base. As can be seen in Fig. 3, a chemical processing plant has been included in the initial configuration. This facility will be used to determine the extent to which usable resources can be extracted from lunar soils. Extensive selenology experiments can be carried out using the rovers and trailers from the reconnaissance mission. The trailer facilities can be enhanced using equipment brought from Earth and excursions in these units can be used to place automated sensing packages at sites far removed from the base. Radio astronomy and VLBI experiments in particular can be carried out from a base of this scale. Finally, life science experiments in health maintenance and food production could be conducted. As operational experience is gained with the base, each of the experiments cited above can be expanded and enhanced. Experiments in high-energy physics, gravity

Table 1. Suggested Strategy for Deployment and Initial Operation of a Lunar Science Base

No.	Mission Description	Personnel		LEM Status*		No. of People On the Moon*
		Going	Returning	In LLO	On Surface	
1	Deploy interface module and power plant	0	0	1	0	0
2	Deploy laboratory module	0	0	1	0	0
3	Deploy habitat module and processing plant	0	0	1	0	0
4	Deploy resources module	0	0	1	0	0
5	Deploy second LEM	0	0	2	0	0
6	Send first construction team	4	0	1	1	4
7	Send second construction team	3	0	1	1	7
8	Switch 1st construction team and 1st station team	4	4	1	1	7
9	Switch 2nd construction team and 2nd station team	3	3	1	1	7

*At completion of mission

waves, and space plasmas can also be added in such a way as to take advantage of the unique conditions found on the lunar surface. These experiments are complementary to those already being conducted at the space station (Science Applications International Corp., 1984b).

SUMMARY

This study has highlighted two missions designed to establish a permanent research facility on the lunar surface. A manned reconnaissance mission was believed to be necessary to conduct final siting of the base prior to its construction. This first mission is entirely complementary to the later operational base since all equipment developed for reconnaissance would be used at the permanent facility. Table 2 shows a cost breakdown

Table 2. Manned Lunar Surface Base Cost (Present Year $B)

	Reconnaissance	Surface Base	Total
Surface modules			10.2
Shelter	0.1		
Trailer (2)	1.5		
Rover (2)	1.4		
Permanent modules (4)		5.8	
Chemical processing plant		0.9	
Nuclear power plant		0.5	
Propulsion stages			16.4
Lunar excursion module	2.7	1.4	
Lunar logistics lander	2.7	3.6	
OTVs	0.8	3.0	
OTV crew module	1.6	0.6	
On-orbit assembly and test	1.0		1.0
STS			10.0
Reconnaissance (12 launches)	1.3		
Base deployment (25 launches)		2.7	
Base operations (18 launches per year)		6.0	
Operations*			14.5
Mission control center	0.5	2.1	
Training/operations development/ management	2.0	5.0	
Mission (orbital and flight operations)	0.7	3.1	
Logistics	0.2	0.9	
Totals	16.5	35.6*	52.1

*Includes 3^y ops at surface base

for both of these missions, assuming the use of existing or near-term technology. It should be noted that the cost of the surface base includes three years of operations. The base could and probably would function for a much longer time than this. The total cost of approximately $52 billion would only be slightly less without the initial reconnaissance mission. For comparison, the cost of the Apollo Program in equivalent dollars is $75 billion. Both the concept and the cost suggest that this facility is programmatically feasible and would make a worthwhile national or international goal in the post space station era.

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MERITS OF A LUNAR POLAR BASE LOCATION

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Because the Moon's spin axis is inclined only 1½ degrees off normal to the plane of the ecliptic, there are no seasons; there are regions near the poles in permanent shadow and, possibly, regions where the Sun never fully sets. The permanent-shadow regions theoretically should be very cold and, with continuous sunlight nearby, are inviting sites for thermodynamic systems. If located near a pole, a lunar base can have solar electric power and piped-in solar illumination continuously available except during occasional solar eclipses. Habitat and farm conditions in underground facilities are easily kept constant. Access from lunar orbit is good because a polar orbiter would pass overhead about every two hours. Waste heat rejection should be much easier than in the widely varying thermal environment of lower latitudes. Polar cold-trapped volatiles may be available. Even if useful volatiles are not naturally present, the cold regions provide convenient storage sites for volatile products of material processing in the base—important when transport logistics are considered. The polar sites offer excellent astronomical opportunities: half of the sky is continuously visible from each pole, and cryogenic instruments can readily be operated there. A geochemical and topographical survey from polar orbit is the next logical step in determining the real merits of a polar base site on the Moon.

INTRODUCTION

The Moon's polar regions offer some unique advantages for human living. Because the Moon's polar axis is inclined only 1½ degrees off normal to the plane of the ecliptic (Fig. 1), there are no seasons on the Moon. Near both poles, portions of the surface such as crater bottoms are permanently dark, and there may be places—this is not a certainty—where some part of the solar disk is always above the horizon. A solar power plant built upon such a "mountain of perpetual light" would supply continuous power except during brief solar eclipses when the Earth would shut off the sunlight.

This circumstance, unique to polar sites, is sufficient justification for considering all aspects, both positive and negative, of locating bases at the poles. Previous studies of this and related subjects are reported in Watson *et al.* (1961), Gary *et al.* (1965), Arnold (1979), Culbertson (1961), Dalton and Hohmann (1972), Green (1978), and Burke (1977, 1978).

WHAT IS KNOWN AND UNKNOWN ABOUT THE LUNAR POLES

Figures 2 and 3 are the best available overhead photos of the lunar polar regions, obtained by Lunar Orbiter IV in 1967. The ground resolution in these images is of the order of 100 m and, of course, nothing is seen in the large shadowed areas. Though the low sun angle exaggerates the roughness of the surface, it is true that the topography at both poles is fairly rugged for the Moon; the surface morphology is that of the ancient, heavily-cratered highlands. Geologic maps of the polar regions have been published based

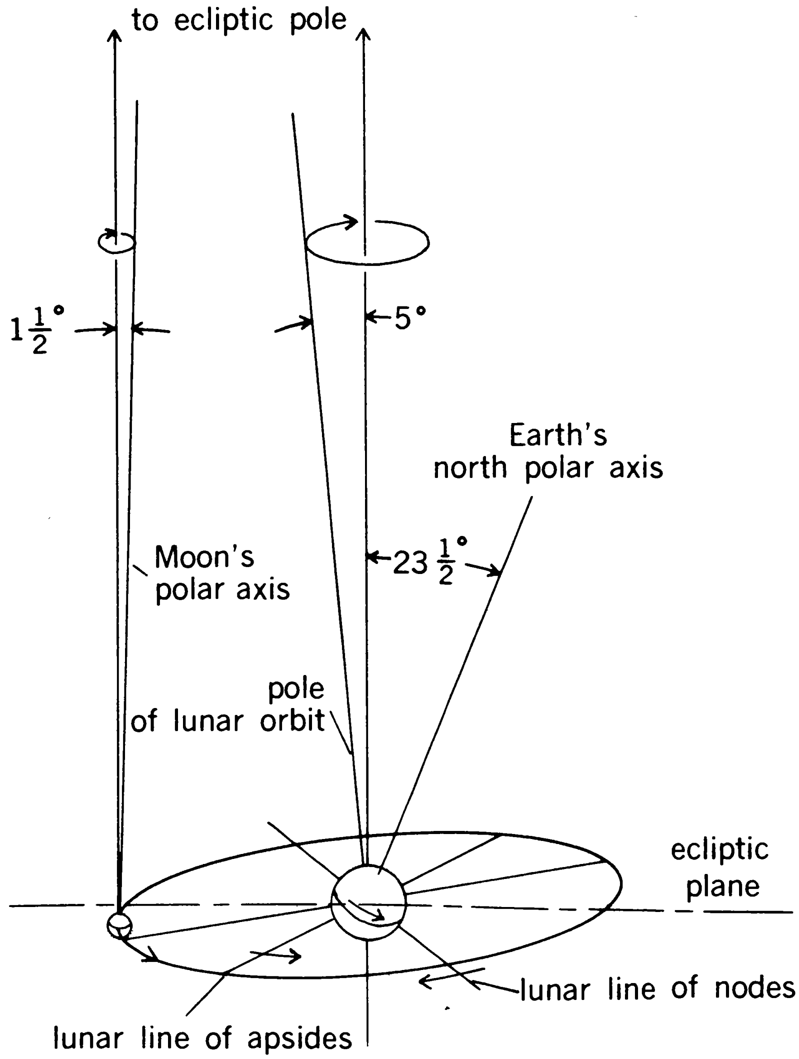

Figure 1. An illustration of the motions of Earth and Moon with reference to the pole of the ecliptic. While Earth's polar axis is inclined 23½ degrees and precesses with a period of about 25,000 years, giving us seasons and the progression of signs of the Zodiac, the Moon's polar axis is inclined only 1½ degrees. Thus, despite the five-degree inclination of the lunar orbit plane and the eighteen-year precession of the lunar polar axis and orbit plane (as discovered in the 18th century by Cassini), sunlight is always nearly horizontal at the lunar poles.

on the lunar orbiter photos (Lucchitta, 1978; Wilhelms *et al.*, 1979). Geochemical mapping, however, awaits the flight of a remote-sensing polar orbiter.

By analogy with the data obtained at lower latitudes by Apollo and other missions, we have reason to believe that lunar highland rocks and soils, rather than mare types, will predominate in the polar regions, with the south pole having the more strongly highland character. Thus, the industrial resources peculiar to the maria may not be abundant near the poles. Detailed surface properties will, however, remain unknown pending orbital and surface exploration. At lower latitudes there is a twilight haze, detected by both U.S. and Soviet spacecraft, that is believed to be due to small particles moving in electrostatic suspension within a few meters of the surface (De and Criswell, 1977). This particle haze and also some of the gas clouds detected by ALSEP instruments are associated with terminator passage (sunrise and sunset). Since the terminator is always present in the polar regions, the local environment due to these particle and gas effects may be different

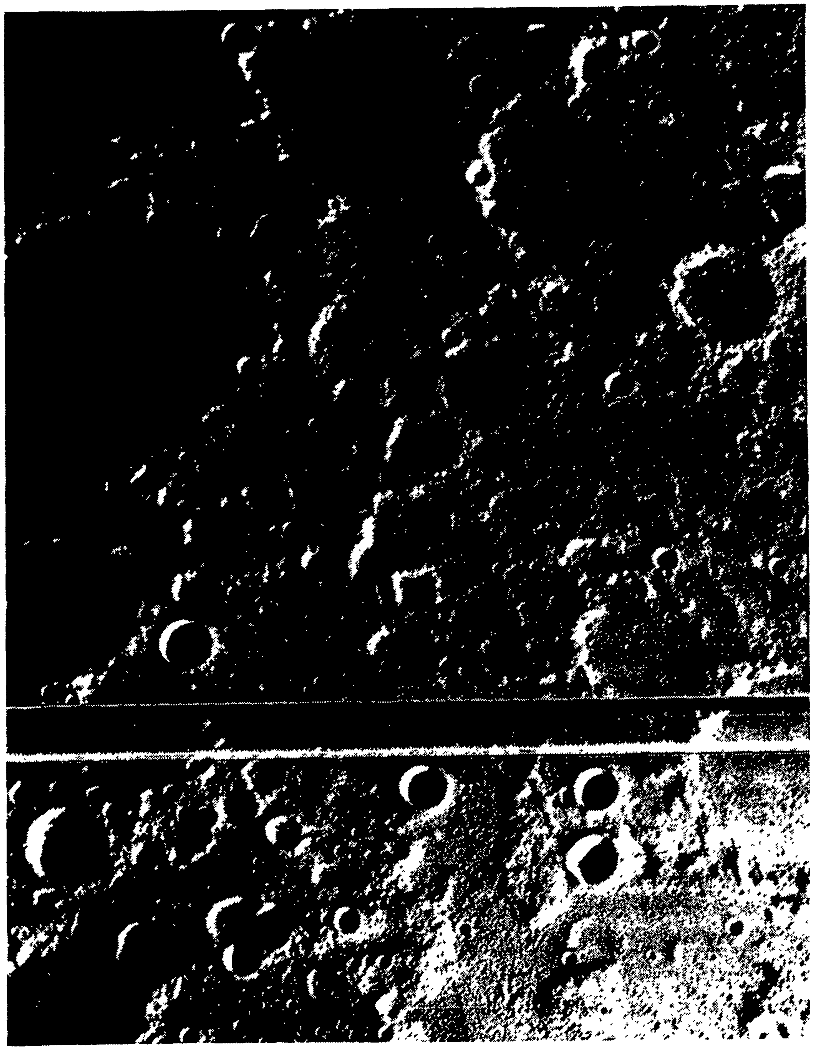

Figure 2. North polar region of the Moon. Craters Peary and Byrd, at top center and upper right, are about 80 km across. Pole is at upper left.

and may, for example, influence the choice of sites for astronomical instruments where minimizing scattered light is a criterion.

An important unknown about the polar regions is the presence or absence of surface and subsurface ices (Watson *et al.*, 1969; Arnold, 1979; Lanzerotti *et al.*, 1981). Very low temperatures must prevail in the permanently-shadowed regions (perhaps as low as 40 K), raising the prospect that trapped water and other ices could survive there over geologic time. However, there is no way, other than spacecraft exploration, to ascertain whether or not useful quantities of such ices are present. If they are, they will provide an overwhelming reason for locating at least some part of a base complex near a pole.

ADVANTAGES, OTHER THAN POSSIBLE NATIVE VOLATILES, OF A POLAR BASE LOCATION

The dominant advantage of a polar site, from the standpoint of habitat design, is the constant thermal and illumination environment. Anywhere else on the Moon, the

Figure 3. South polar region of the Moon. Crater Amundsen, near center, is about 100 km across. Pole is about halfway from Amundsen to bottom of frame.

base design must cope with two-week days and two-week nights. Engineering solutions to this problem, including thermal insulation and control measures and energy management, are available in principle; some of them have even been used on the Moon. For example, the Soviet Lunokhod rovers each had a hinged solar panel that served also as a thermal cover at night when closed, and they had radio-isotope heaters to maintain internal temperatures through the night. However, in a human habitat—especially one that includes agriculture, even on an early experimental scale—continuous sunlight and a stable thermal environment would permit much simpler support systems and would remove several possible sources of failure.

Figure 4 is an artist's concept for an underground habitat powered, warmed, and illuminated by the nearly-horizontal sunlight at a lunar pole. A heliostat mirror directs the solar beam into a periscope-like tunnel whose shape provides shielding against cosmic and solar ionizing radiation. Within the base, other mirrors direct the sunlight as desired,

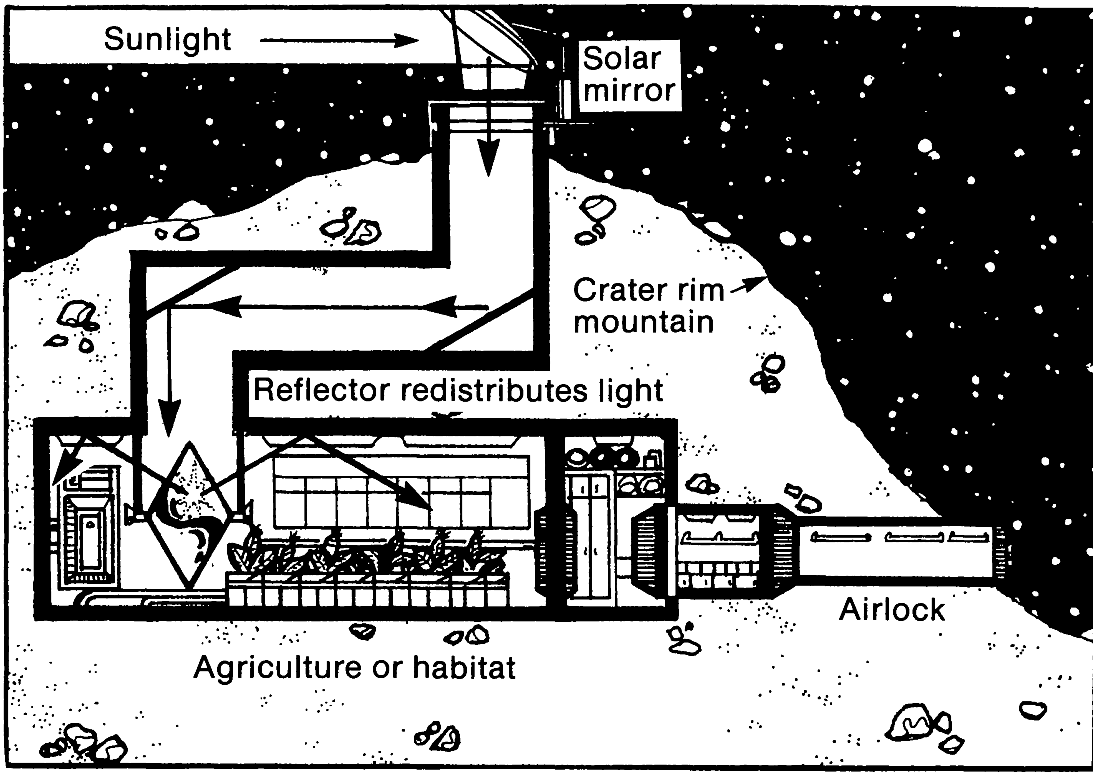

Figure 4. Underground polar habitat with sunlight piped in from heliostat. Drawing by L. Ortiz, provided courtesy of NASA.

avoiding some of the energy conversions that would otherwise be needed. In Fig. 5, a solar power tower is shown. On a common base, rotating one-half degree per hour to point continuously toward the Sun, are installed a heliostat mirror for a solar furnace, a cylindrical collector for lower-temperature heat, and a solar photovoltaic panel. With systems of this sort for energy supply and with a small reserve power plant to handle solar eclipses (whose duration is typically a couple of hours) a base should be able to operate with a nearly constant energy flow. When one considers this energy throughput another advantage of the polar site appears: heat rejection at the bottom end of the thermodynamic cycle may well be done through a surface radiating to space, insulated on its bottom side, and located in a cold, permanently-shadowed crater bottom, thus simplifying and reducing the size of this large and important system element.

Apart from these thermal and illumination advantages, other benefits may be found in the polar regions. Even if no natural ices are present, cold products can be kept in the dark crater bottoms—an important opportunity if the base's functions include producing and storing volatile life-support or propellant materials. At any warmer location, heavy pressure tanks would be needed for such storage. Because the natural equilibrium temperatures in the polar cold traps are unknown now, it is too early to tell how important this storage prospect may be. Storage of water as ice is likely to be practical; storage of liquid or solid oxygen may or may not be; storage of hydrogen will probably require containers.

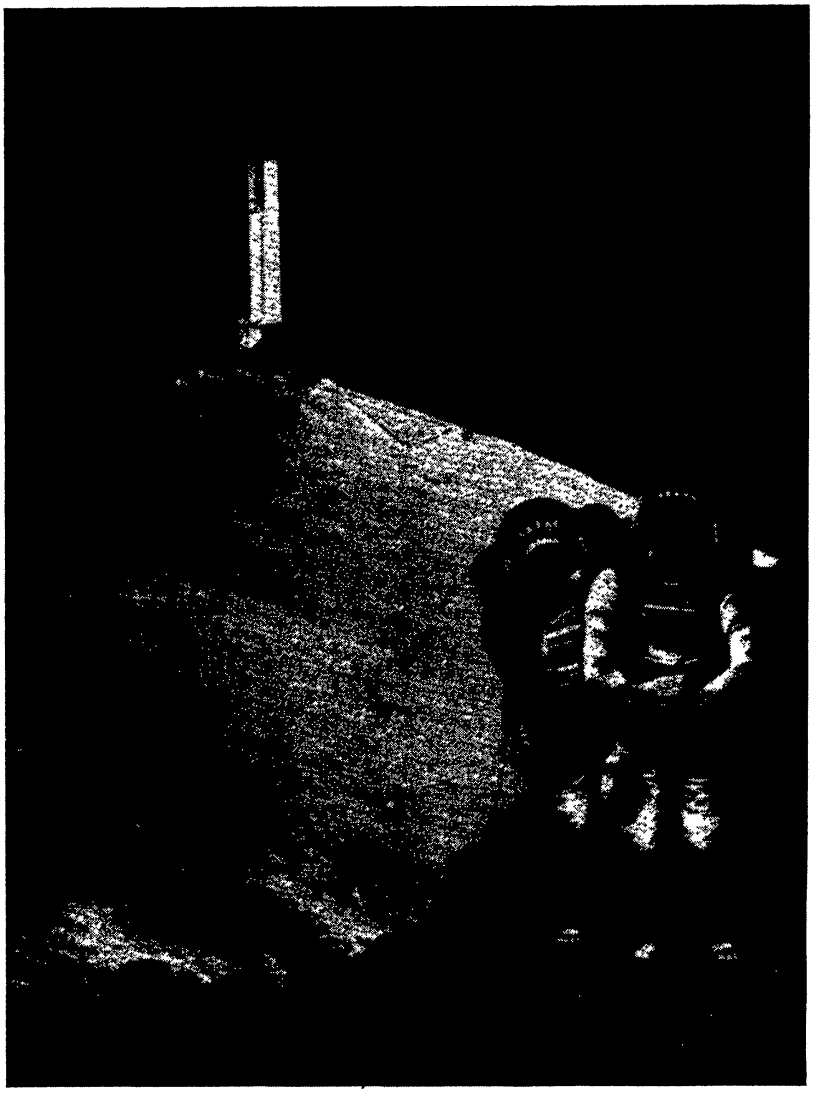

Figure 5. Solar power tower in permanent sunlight near a lunar pole. Painting by Maralyn Vicary, provided courtesy of NASA.

The equilibrium temperature of such a passive storage unit would be set by the balance among heat generated locally, natural heat flow from the lunar interior upward through foundation insulation, scattered sunlight from any lunar surfaces or other nearby illuminated objects not shielded from the radiator's view, and energy from stars and other cosmic sources falling on the radiator. Temperatures below 100 K should be readily achieved [as suggested by radio brightness temperature measurements such as those of Gary *et al.* (1965)], but how low it is ultimately feasible to go, with practical lunar engineering design solutions, is at present unknown.

Another inviting aspect of the polar sites is their potential with respect to astronomy. Cryogenic telescopes located in continuous darkness could view celestial objects for as long as desired—observing, of course, only a bit less than half of the sky from each pole. If a choice of poles had to be made, the south pole would probably be preferred because the southern sky is less explored and includes unique objects such as the galactic center.

For radio astronomy, a polar location seems to offer no particular advantages over a lunar farside site, shielded from the radio noise of Earth and located at low latitude for viewing the entire sky. However, if both poles are occupied it may be more convenient to locate radio telescopes there, and the rough topography probably provides sites adequately occulted from Earth.

A solar tower telescope is another astronomical instrument that would benefit from a polar location, from whence continuous viewing of the Sun (as is now being done during the austral summer from Antarctica) would be possible. However, the advantages, if any, of such installations relative to observatories in heliocentric orbit are debatable and depend on assumptions about the supporting infra-structure. For example, a fixed lunar site offers refurbishment and maintenance advantages if, and only if, the base is capable of supporting those functions. This raises the familiar question of how to allocate and compare costs for orbital versus lunar observatories.

Another advantage, available at the poles and at the equator but nowhere else on the Moon, is quick access to and from lunar orbit. A lunar-orbiting space station in polar orbit would pass over a polar base every two hours, facilitating the schedules of both routine and emergency transport from the lunar surface to lunar and Earth orbits. Also, a polar orbit for the lunar space station is advantageous because it gives overhead coverage and access, from time to time, for expeditions anywhere on the Moon.

DISADVANTAGES OF LIVING AT THE POLES

The lunar environment, unfamiliar at best, will be even stranger for the first pioneers who settle near the poles. As the glaring sun creeps endlessly around on the horizon, most surfaces will be dark, unless illuminated by lights or mirrors for local work. Earth will hover in one direction moving from side to side and up and down a few degrees on the sky but remaining below the horizon from many nearby regions. Communications to and from Earth will, therefore, have to involve orbital or surface relays. While these are quite practical, they should be carefully designed to preserve the radio silence of the lunar farside, which, being shielded from the radio noise of Earth, is a prime site for radio astronomy and searches for radio evidence of extraterrestrial intelligence (SETI). Whether or not the polar environment presents any real hazard to human activity remains to be seen; the question can probably be answered in part by simulation experiments on Earth.

Accommodations to the natural disadvantages of a polar base site seem rather straightforward and unlikely to outweigh the many advantages of living there. We should explore the Moon's polar regions both from orbit and on the surface, and we should seriously consider one or both poles as base locations. Because the regions of primary interest are likely to be small, with dimensions of only tens or hundreds of kilometers on the lunar surface, it will probably be important to control access to them and to protect their unique natural environments under some accepted, international, legal regime. What a happy outcome it would be if international crews occupied both lunar poles, exploiting the experimental advantages of each and building toward the time when humanity

can fully realize the benefits of living comfortably and productively in these unique environments of the Moon.

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NUCLEAR ENERGY—KEY TO LUNAR DEVELOPMENT

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The Moon will play a very central role in man's exploitation of cislunar space. Energy, especially nuclear energy in the form of advanced radioisotope and fission reactor power systems, will play an equally major role in any lunar development program. This paper explores the relationship between man's successful return to the Moon as a permanent inhabitant and the use of nuclear energy. It is done within the context of a five-stage lunar development scenario. The technical discussion extends from the use of radioisotope-powered vehicles for mineral resource exploration and automated site preparation, to the reactor-powered early manned bases in which scientific investigations and prototype manufacturing projects are undertaken, to the rise of a fully autonomous lunar civilization, nourished by its own nuclear fuel cycle. If the use of nuclear energy is properly integrated into lunar development strategies, it will not only greatly facilitate the industrial development of the Moon, but may also represent a major lunar industry in itself. It is distinctly possible that very large nuclear-powered communication platforms located throughout cislunar space will be designed, constructed, and fueled by future lunar inhabitants. The same may be said for the advanced multimegawatt class reactors that will power electric propulsion vehicles, carrying human explorers to Mars and sophisticated robot explorers to the outer reaches of our solar system and beyond. The Moon is humanity's gateway to the Universe—and nuclear energy is the technical key to that gate!

INTRODUCTION

Energy is key to the exploration and development of lunar resources. High space transportation costs from Earth make it necessary to utilize energy systems that minimize mass; the clever use of *in situ* lunar materials is another way to minimize the amount of equipment that must be transported from the Earth to the Moon. An initial use of Moon materials will be used for building shields or barriers around nuclear power plants. Eventually, as lunar bases grow, their mining and manufacturing capabilities will take further advantage of native lunar resources to meet expanding energy requirements.

The development of man's permanent civilization on the Moon can be partitioned into five distinct stages: (1) automated surface exploration/site preparation, (2) the initial lunar base, (3) early lunar settlements, (4) mature lunar settlements, and (5) the autonomous lunar civilization.

STAGES OF LUNAR DEVELOPMENT AND POWER NEEDS

The stages of lunar development are given in Table 1 (Angelo and Buden, 1983), and scientific objectives are given in more detail in Table 2.

Automated Surface Exploration/Site Preparation

The first objective is to complete the mapping of the Moon's surface and to establish the chemical, mineralogical, and petrological characteristics of the Moon in order to locate optimal locations for permanent manned bases. The lunar polar regions have not been explored, so the presence or lack of surface water (ice and other frozen volatiles) must still be verified. A Lunar Polar Orbiter could be used to complete this mapping (Duke *et al.,* 1984). Power requirements are quite low (hundreds of watts); they can probably be met using existing solar energy photovoltaic technology.

Surface and subsurface exploration can be achieved with both manned and unmanned rovers. The early rovers might be solar powered, instead of battery powered as in the Apollo program, to provide longer operating times. This choice, however, limits exploration to the lunar day (14 Earth-days long) or requires mass intensive energy storage systems. Drill/manipulator robotic systems could be used to drill holes to determine subsurface

Table 1. Stages of Lunar Development

Stages	Population
Automated Surface Exploration/Site Preparation	Robotic
Detailed surface exploration	2-5 people (semi-permanent)
Subsurface exploration	
Site preparations for initial lunar base	
Initial Lunar Base	6-12 people (permanent)
Initial scientific base	
Expanded resource exploration	
Extraterrestrial materials experiments	
Early Lunar Settlements	100-1000 people
Expanded research activities	
Prototype lunar materials processing	
Start of lunar agriculture	
Materials source for space station industrialization	
Mature Lunar Settlement	1000-10,000 people
Large scale mining and materials processing	
Manufacture products	
Cislunar trading	
Limited food production	
Autonomous Lunar Civilization	10,000-100,000 people
Self-sufficiency in raw materials and manufactured goods	
Self-sufficiency in food production	
Lunar fuel cycle	
Radioisotope generators and reactor fuel	
Lunar waste repository	

Table 2. Prioritized Scientific Objectives for Continued Exploration of the Moon

Objectives
1. Assessment of global resources, including a search for global volatiles at the poles
2. Intensive study of local areas to establish the chemical, mineralogical, and petrological character of the lunar surface
3. Measurement of global figure and surface topography
4. Exploration of the nature and dynamics of the Moon's interior
5. Establishment of the Moon's gravitational field

mineral content. Either conventional drilling techniques or hot-dry rock techniques as developed in the subterrene program at Los Alamos National Laboratory might be used during this surface exploration to explore more effectively the subsurface resource potential of the Moon (Hanold *et al.*, 1977).

This stage would culminate in the establishment of a site for a permanent lunar base (see Fig. 1). Site preparation will probably need robotic regolith-moving equipment. Power levels, based on construction equipment built for space transportation, are expected to be a few kilowatts. Part of the site preparation may include a barrier composed of regolith material that will function as a radiation shield for a nuclear reactor. Power levels on the order of a hundred kilowatts will be needed once an initial lunar base is established.

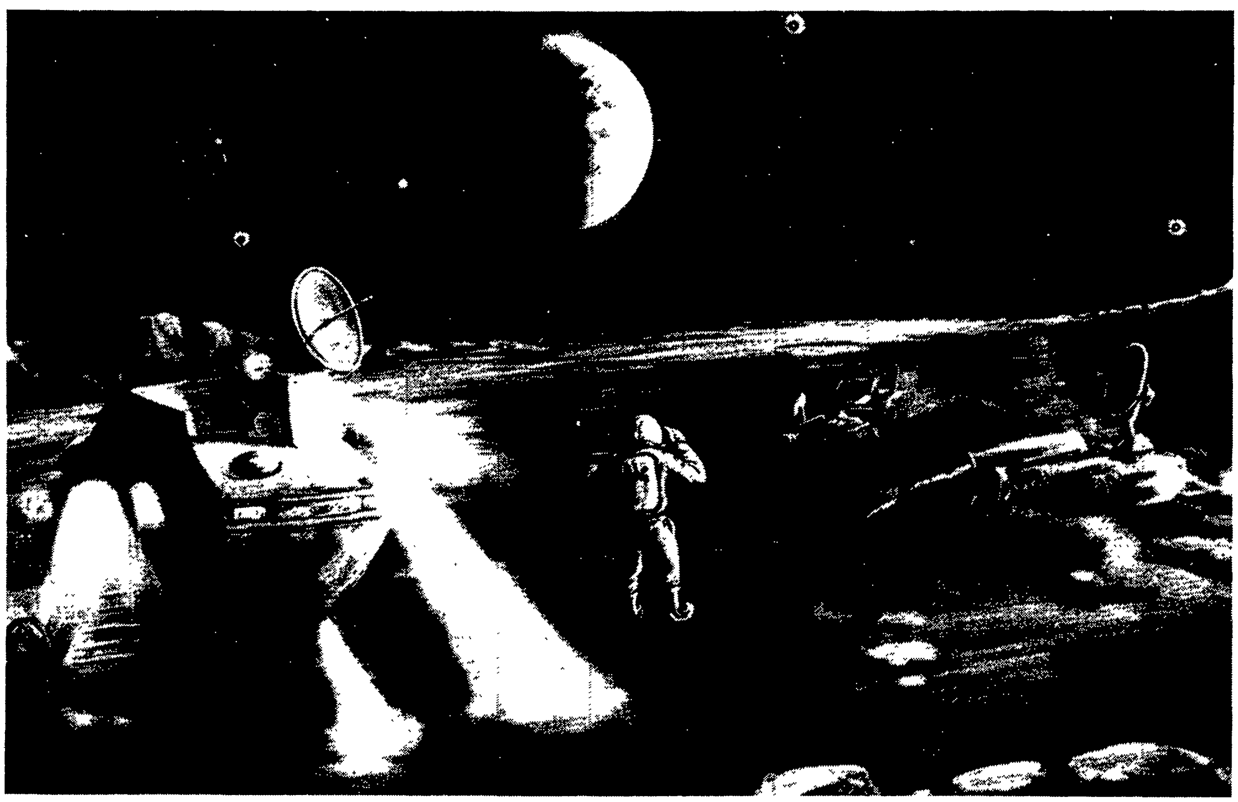

Figure 1. Automated site preparation.

Initial Lunar Base

The initial lunar base will serve as a science center to better understand the Moon and our solar system. This base will also support investigations concerning processes for mining lunar materials, materials beneficiation, and manufacturing (see Fig. 2). Oxygen is frequently mentioned as a leading candidate for lunar manufacturing, both because it is abundant in lunar rocks and because it has a high value as a chemical propellant in space transportation systems. A major goal of this stage is to learn how to live and work on the lunar surface. The initial lunar base is expected to require power levels similar to the early space station—on the order of 100 kWe.

Early Lunar Settlements

As the initial lunar bases expand their activities, selected, small-scale mining and beneficiation of lunar materials will take place (see Fig. 3). Selected Moon materials will start being exported to support overall space industrialization activities (see Fig. 4 for one scenario). In addition, certain products will be manufactured on the Moon. The lunar population, or "selenians," will number from 100 to 1000 permanent inhabitants. This

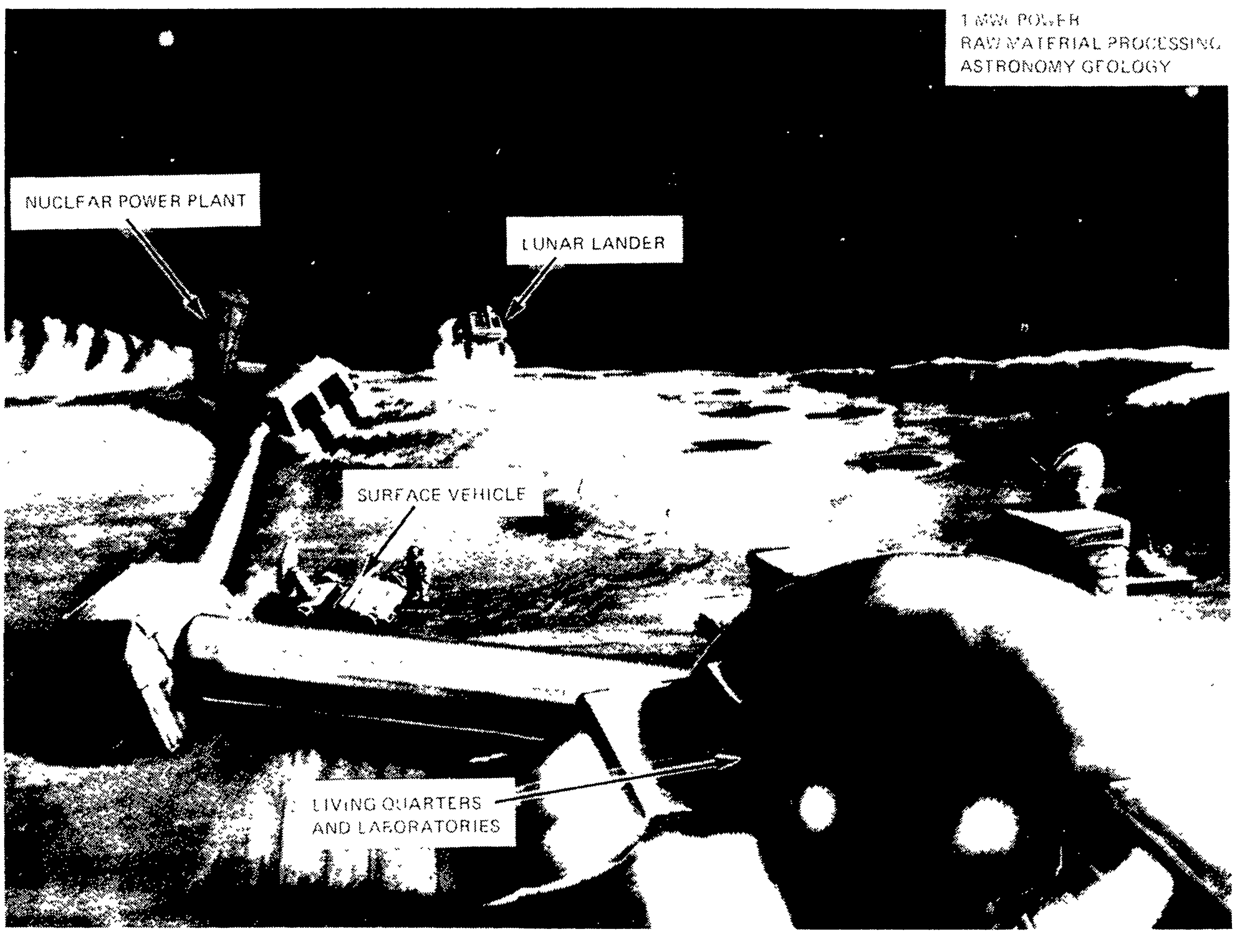

Figure 2. Early lunar base.

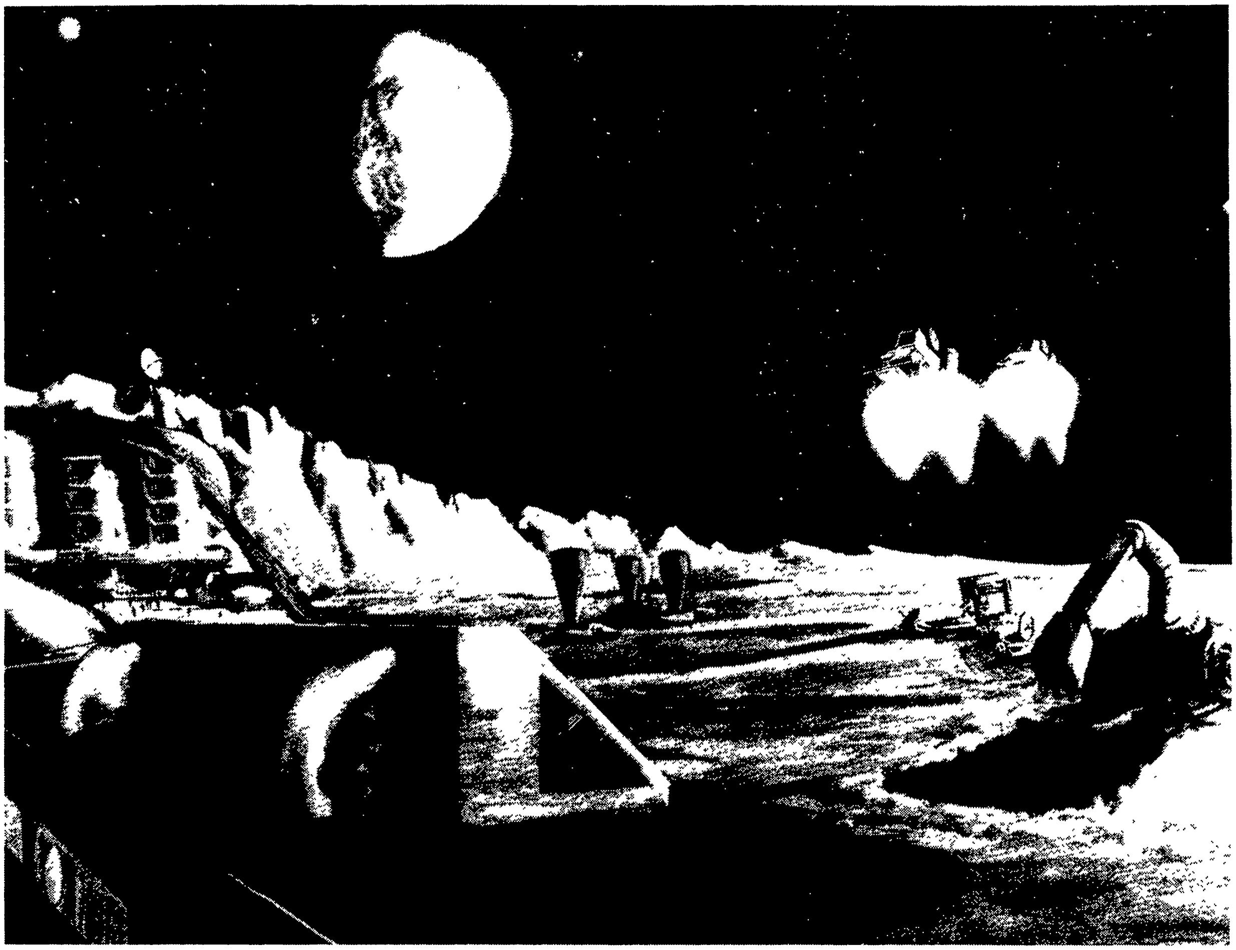

Figure 3. Early lunar settlements.

time period will witness the initiation of extraterrestrial agriculture, with food being produced in special lunar greenhouses to accomodate the expanding population. Power consumption during this period of lunar development is expected to be in the megawatts, based on the number of inhabitants present and on-going activities.

Mature Lunar Settlements

Nourished by native resources, the lunar population will eventually swell to 10,000 or more permanent inhabitants (see Fig. 5). A semi-autonomous status will be achieved as much of the manufactured goods and significant quantities of food will be produced on the Moon for both domestic consumption and "export." Power demand will reach tens of megawatts and parts of a nuclear power industry will be in place. The power level estimates are based on the size of population and power demands of a similar population on Earth. Lunar settlements will be more dependent on electric power because of the greater limitations of alternate energy sources.

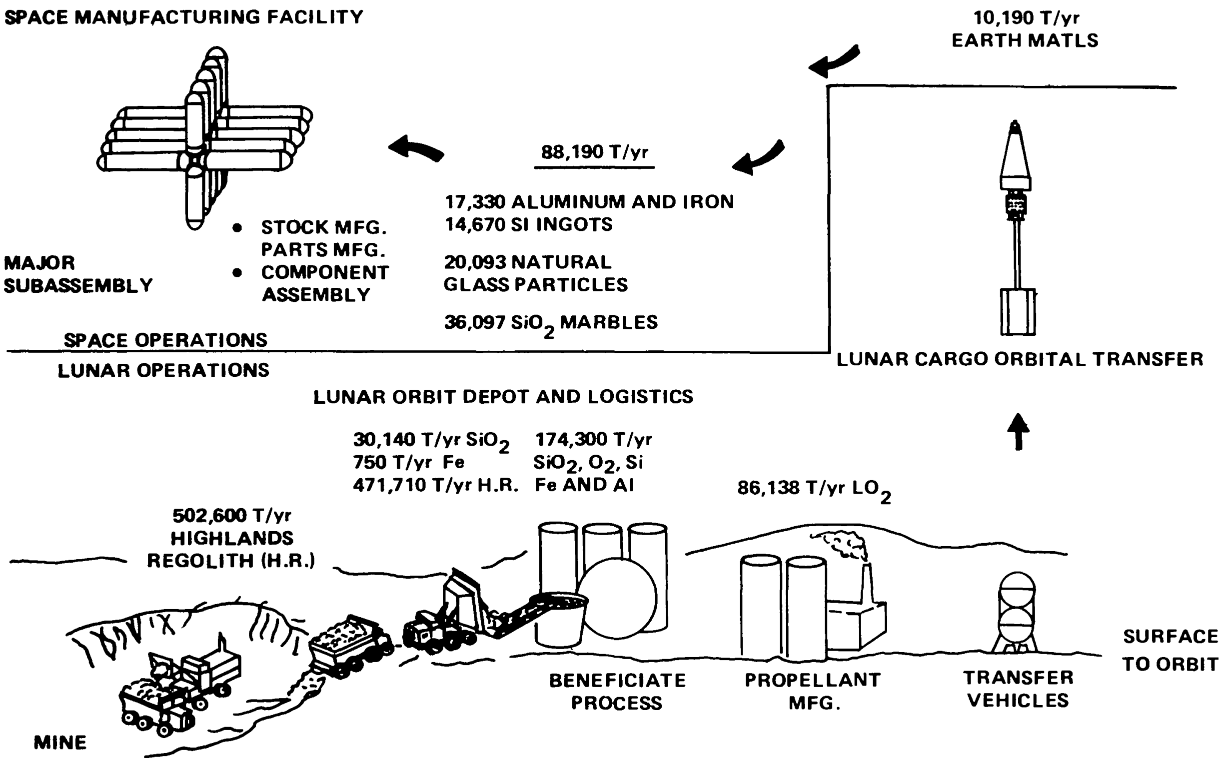

Figure 4. General processing and space-based manufacturing showing flow of lunar materials.

Autonomous Lunar Civilization

The lunar civilization will reach maturity (see Fig. 6). Its population will no longer be dependent on Earth for manufactured and agricultural goods. With an energy-rich, dynamic lunar civilization now feeding further expansion into heliocentric space, the selenians will eventually become the space-faring portion of the human species. Hundreds of magawatts of power will be needed in this phase to provide the necessary energy for such a large population.

In the full scale exploitation of cislunar space and the Moon, nuclear electric propulsion systems (NEPS) will serve a critical enabling role in the efficient transport of massive, non-priority cargoes (Buden and Garrison, 1985). NEPS will serve not only as the propulsive means of placing a massive payload in an appropriate operating orbit, but once the operational location is reached the nuclear reactor would then serve as the prime power supply for many years of continuous, profit-making operation of the payload. Nuclear electric propulsion systems could also be used as reusable orbital transfer vehicles (OTVs) or "space tugs." These propulsive workhorses of tomorrow would gently move massive cargoes, supplies and materials, large and fragile space systems that had been assembled in lunar orbit, or even entire (unoccupied) habitats, and ferry these cargoes to their final

destinations throughout cislunar space. Habitat fabrication may be a major lunar industry by the 22nd Century.

NUCLEAR POWER OPTIONS

The various stages of lunar development and associated power requirements are given in Table 3.

Because the Moon experiences long diurnal cycles (a 14 Earth-day "day" and a 14 Earth-day "night") solar energy becomes an awkward energy source to rely on in a continuously inhabited and operated lunar settlement. This is mainly because massive energy storage devices would be needed for power in the night cycle. Nuclear energy offers a relatively compact power source that is not affected by the diurnal day/night cycle, and the technology should be available if current development plans proceed as now scheduled.

Radioisotope generators have been used where long life, high reliability, solar independence, and operation in severe environments are critical. These use the spontaneous

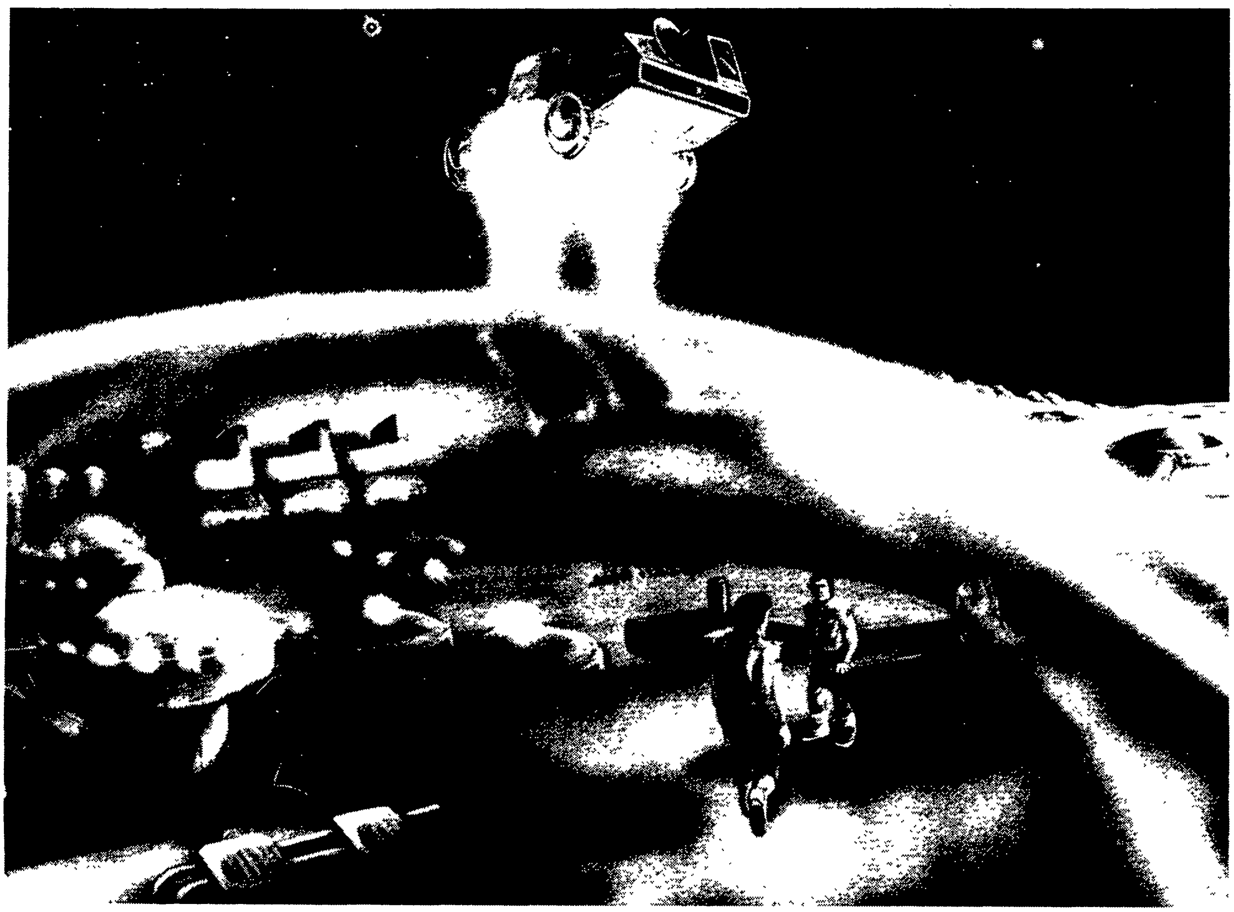

Figure 5. Semi-autonomous lunar settlement.

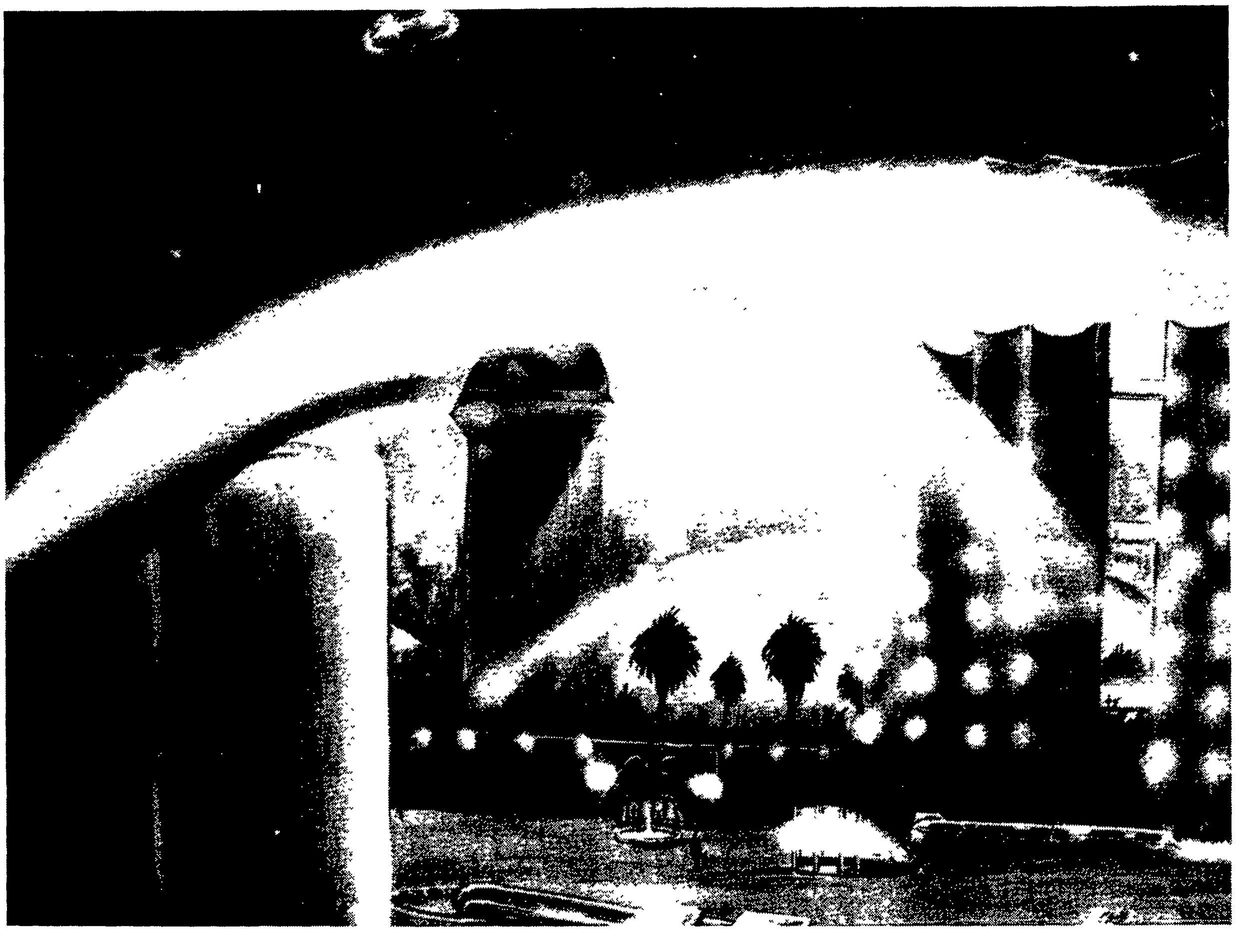

Figure 6. Autonomous lunar civilization.

decay of plutonium-238 as a heat source. The energy has traditionally been converted to electricity by means of thermoelectrics placed next to the heat source. Radioisotope generators have been launched in 21 spacecraft, beginning with the successful flight of a SNAP-3B power source in 1961. Their reliability and long life is demonstrated by the Pioneer satellite, which after 11 years of operation left our solar system still in a functioning state. The recent magnificent pictures of Saturn taken from the Voyager spacecraft, powered by radioisotope generators, are also testimonials to the longevity and reliability of this type of power supply. Improved versions of the generators with thermoelectric electrical conversion devices will increase their performance. However, radioisotope thermoelectric generators will probably be restricted to under 500 W. Higher power levels of maybe 1-10 kW are possible by using dynamic electric converters for power conversions. A 1.3 kW version has been tested for several thousand hours prior to program termination (Bennett *et al.,* 1981).

For initial lunar bases and early lunar settlements, the SP-100 Program technology is applicable. If we use native lunar materials for radiation shield, all other nuclear cycle components can be transported from Earth with contemporary space transportation system

Table 3. Stages of Lunar Development and Power Requirements

Stage	Activity	Power Levels	Probable Nuclear Power Supply
1	Automated Surface Exploration/ Site Preparation	kWe	Radioisotope generators
2	Initial Lunar Base (6–12 persons)	~100 kWe	Nuclear Reactor (SP-100)
3	Early Lunar Settlements (100–1000 persons)	~1 MWe	Expanded SP-100 (Advanced Design)
4	Mature Lunar Settlement (~10,000 persons)	~100 MWe	Nuclear Reactor (Advanced Design)
5	Autonomous Lunar Civilization (Self-sufficient Lunar Economy: >100,000 persons)	hundreds of MWe	Nuclear Reactors (Advanced Design, Complete Lunar Nuclear Fuel Cycle)

vehicles, *i.e.*, Shuttle plus advanced orbital transfer vehicles. The SP-100 Program is a joint program of the Departments of Defense and Energy and NASA to develop space nuclear power systems technology. Following screening of over a hundred potential space nuclear power system concepts by the SP-100 Program, the field has now been narrowed to three candidate systems (Ambrus *et al.*, 1984).

One concept uses a fast spectrum, lithium-cooled pin-type fuel element reactor coupled to thermoelectrics for power conversion (see Fig. 7). The reactor, which is a right circular cylinder, approximately one meter in diameter and one meter high, is at the apex of the conical structure. It is controlled by twelve rotatable drums, each with a section of absorbing material and a section of reflective material, to control the criticality level. Control of the reactor is maintained by properly positioning the drums. The shield is mounted directly behind the reactor and consists of both a gamma and a neutron shield. Thermal transport is accomplished by a lithium working fluid that is pumped by a thermoelectrically driven electromagnetic pump. The reactor thermal interface with the heat distribution system is through a set of heat exchangers. Thermoelectric elements are coupled to the internal surfaces of the heat rejection panels and accept heat from the source heat pipe assembly. The heat rejection surfaces are beryllium sheets with titanium potassium heat pipes brazed to the surface to distribute and carry the heat to the deployable panels that are required to provide additional heat rejection surfaces.

A second approach is an in-core thermionic system with a pumped sodium-potassium eutectic coolant. The general arrangement of the in-core thermionic space power system design is shown in Fig. 8. The design forms a conical frustum that is 5.8 m long with minor and major diameters of 0.7 m and 3.6 m, respectively. The reactor contains the thermionic fuel element (TFE) converters within a cylindrical vessel, which is completely surrounded by control drums. Electrical power is generated in the space between the tungsten emitter and niobium collector, and the electrical current output is conducted from one cell to the next through the tungsten stem of the emitter and the tantalum transition piece. The NaK primary coolant routing to and from the reactor vessel is arranged so that the hot NaK leaves the reactor at the aft end and the cold NaK is returned

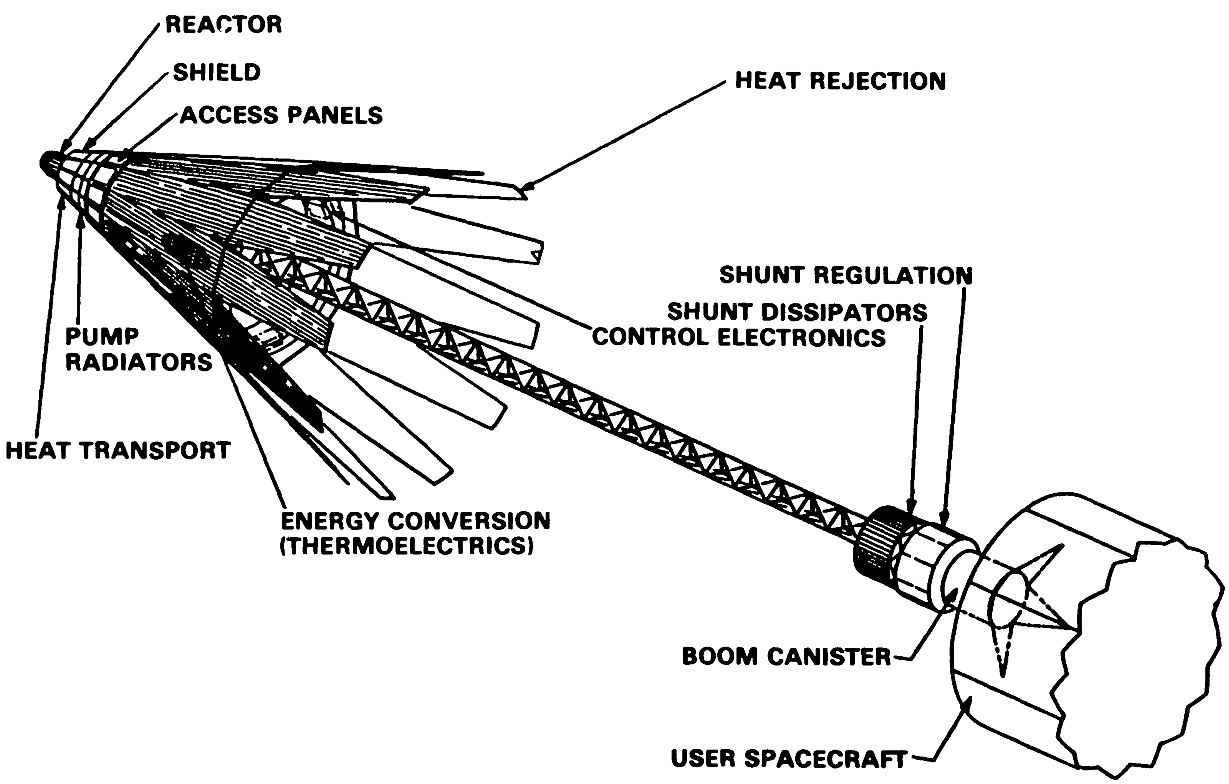

Figure 7. High-temperature reactor with thermoelectric power conversion concept.

to the forward end. The TFE consists of six cells connected in series with end reflectors of BeO. The reactor is also surrounded by an array of long, thin cylindrical reservoirs, which collect and retain the fission gases generated in the reactor core during the operating life of the system. Waste heat is removed from the primary reactor loop through the heat exchanger. The energy is transferred through the heat sink heat exchanger to heat pipes that form the radiating surfaces for rejection of heat to space.

The third approach uses a Stirling engine to convert heat from a lower-temperature (~1000 K), fuel-pin reactor design to electricity (see Fig. 9). This design emphasizes the use of state-of-the-art fuel pins of stainless steel and UO_2 with sodium or sodium potassium eutectic as the working fluid. Such fuel pins have been developed for the breeder reactor program with 1059 days of operation and 8.5% burn-up demonstrated. If the use of stainless steel fuel pins is not possible, a refractory alloy such as Nb-1Zr could be substituted. The reactor can be similar in design to the high-temperature reactor but utilizes lower temperature materials. In Fig. 9, the reactor is constructed as a separate module from the conversion subsystem. Four or five Stirling engines, each rated to deliver 25-33 kWe, are included in the design concept. This provides some redundancy in case of a unit failure. Normally the engines operate at partial power to produce a 100 kWe output. Each engine contains a pair of opposed motion pistons that operate 180° out of phase.

This arrangement eliminates unbalanced linear momentum. Each engine receives heat from a pumped loop connected to the reactor vessel. The heat is supplied to heater heads integral with the engine. Waste heat is removed from the cooler heads and delivered to a liquid-to-heat pipe heat exchanger. The heat pipes, in turn, deliver the waste heat to the radiator, where it is ejected to space.

The advanced stages of lunar settlements will require new reactor designs to satisfy demands for megawatts of power. Power plants will probably need to be refuelable, have a 30-year lifetime, and provide multimegawatts of power. Several technology approaches are possible including solid core, fluid cores, particle bed, and gaseous core reactors. For space, solid-core reactors were most extensively developed as part of the nuclear rocket program. The Rover design featured a graphite-moderated hydrogen-cooled core (Buden and Angelo, 1983). The 93.15% ^{235}U fuel was in the form of UC_2 particles, coated with a pyrolytic graphite. The fuel was arranged in hexagonal-shaped fuel elements, coated with ZrC; each element had 19 coolant channels. Electric power on the order of 100 megawatts could be generated by replacing the rocket thrust nozzle with power conversion equipment. This is a limited-life system, however.

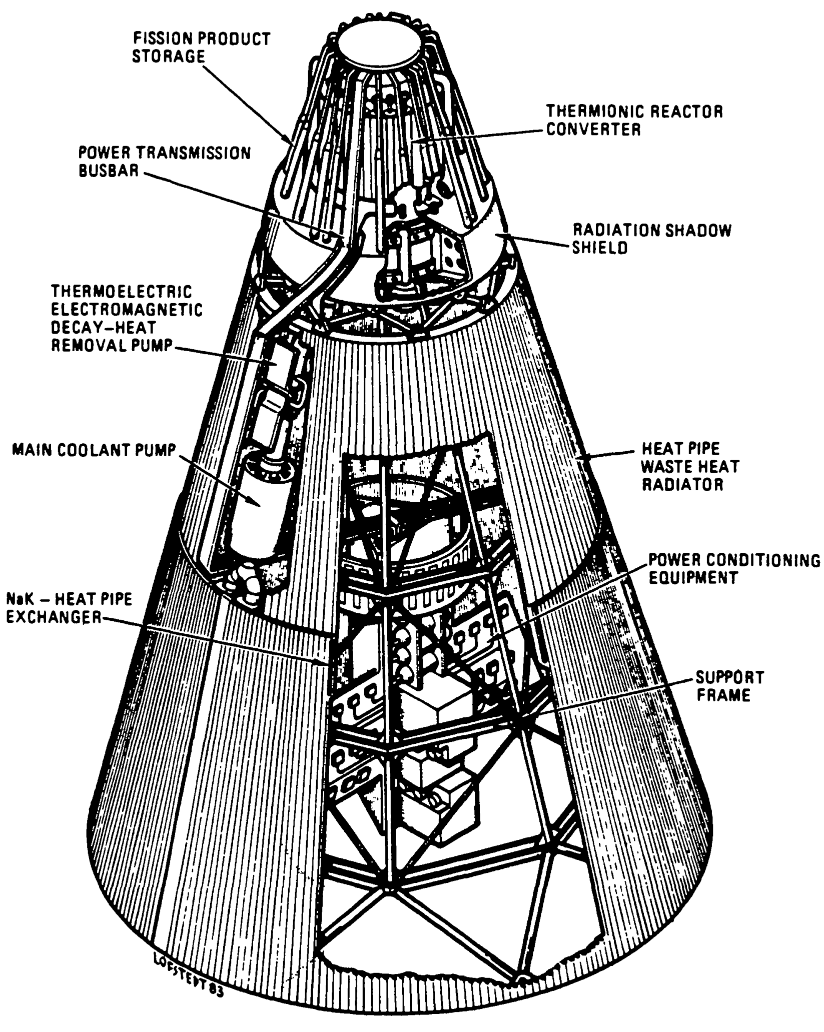

Figure 8. In-core thermionic power plant concept.

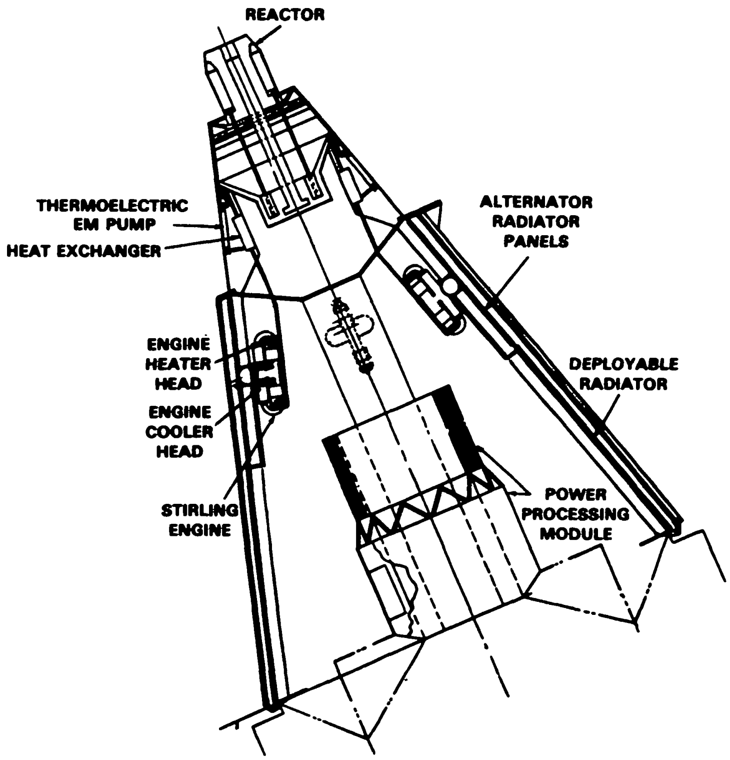

Figure 9. Stirling engine conversion concept.

High-power requirements might also be met by fluidized bed reactors, in either the rotating or fixed-bed forms. The former was investigated as a rocket propulsion concept with modest research effort in fluidized bed reactors carried out from 1960 to 1973.

Another candidate for megawatt-power reactors is a gaseous core reactor system (Thom and Schwenk, 1977). The central component of such a gaseous core reactor is a cavity where the nuclear fuel is in the gaseous state. One reactor concept is an externally moderated cavity assembly that contains the uranium fuel in the gaseous phase. For temperature requirements less than a few thousand degrees Kelvin, the appropriate nuclear fuel would be uranium hexaflouride, UF_6. It is desirable to keep the gaseous fuel separate

Table 4. Average Heavy Nuclide Content of Lunar Regolith

Lunar Surface Material	Lunar Mission	Thorium (ppm)	Uranium (ppm)
Mare	Apollo 11	2.24	1.37
"	Apollo 17	0.82	0.26
"	Apollo 12	6.63	1.61
"	Apollo 15	1.76	0.483
"	Luna 16	1.07	0.300
Highland	Apollo 16	1.87	0.52
"	Luna 20	1.44	0.45
Basin Ejecta	Apollo 14	13.5	3.48
" "	Apollo 15	4.15	0.99
" "	Apollo 17	3.01	0.90

from the cavity walls. This is accomplished through fluid dynamics by using a higher velocity buffer gas along the wall. Power is extracted by convection or radiation heat transfer. Gaseous core reactors offer simple core structures and certain safety and maintainability advantages. The basic research development was completed prior to program termination, including the demonstration of fluid mechanical vortex confinement UF_6 at densities sufficient to sustain nuclear criticality.

New developments in the next several decades will probably have a strong influence on the design approaches for advanced lunar settlements. These designs may more nearly resemble advanced terrestrial reactor central power plant designs. On-line refueling and robotic maintainability features are envisioned with a 30-year or more useful lifetime. Another characteristic of this new generation of lunar reactors would be "inherent safety"—that is, if a malfunction should occur in any part of the power plant, it is designed so that no human operator action or even mechanical automatic control mechanism is needed to achieve a safe condition.

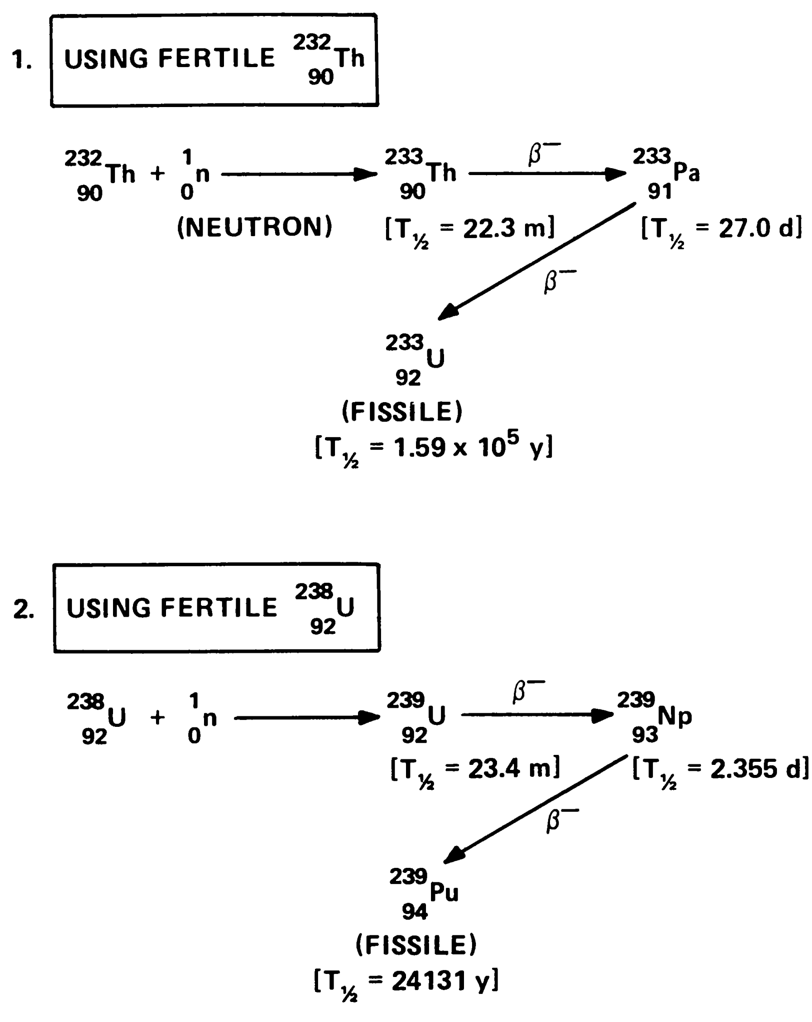

Figure 10. Classic nuclear fuel breeding reactions.

Finally, as the lunar settlement expands and grows, a point will eventually be reached when the lunar civilization, for all practical purposes, becomes fully self-sufficient. As part of this autonomy in Stage 5, a lunar nuclear fuel cycle will evolve, taking advantage of native thorium and uranium minerals [see Table 4 from References (Phinney *et al.*, 1977) and various NASA publications] and the classic nuclear fuel breeding reactions for the "fertile" nuclides, $^{232}_{90}Th$ and $^{238}_{92}U$ (see Fig. 10).

CONCLUSIONS

Power will be the key to lunar development. Without adequate power, the rate and size of lunar development will be severely limited. Nuclear power is a prime technology capable of satisfying these power requirements. Radioisotope generators need further development with an improved electrical conversion system. The SP-100 Program should provide an acceptable power plant for the initial lunar base and early lunar settlements, especially if it satisfies station growth needs. An advanced space power systems now under consideration—including solid core, particle bed, and gaseous core reactor concepts—should be capable of satisfying multimegawatt power needs as lunar civilization evolves.

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NUCLEAR POWERPLANTS FOR LUNAR BASES

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INTRODUCTION

After a hiatus of some ten years, the United States is again involved in development of a nuclear reactor-based electric power plant for space. The SP-100 Program, having been in existence for some two years, has as its goal the development of system concepts and technology for power plants capable of generating 100-1000 kWe for two years initially, with potential growth to seven years. The current phase of the program is devoted to evaluating the various possible design concepts and assessing the status of critical technology. Limited technology development is being carried out as well.

The goal of this phase is to select the most promising system concept and to develop the plan for the system and technology development program that will form the next phase of the project. This phase will begin in FY 1986 with a goal of demonstrating critical technologies, subsystems, and system interfaces for the chosen concept by the early 1990s.

The SP-100 Program is being jointly conducted by DARPA (Defense Advanced Research Projects Agency), NASA, and the Department of Energy with technical leadership provided by the Jet Propulsion Laboratory, NASA/Lewis Research Center, and Los Alamos National Laboratory.

SP-100 CHARACTERISTICS

The SP-100 system is defined as being a nuclear reactor-based electrical power plant designed for space use. Design performance requirements specified for the 100 kWe system under study are listed in Table 1. As noted in the Table, the initial lifetime

Table 1. SP-100 Design Performance Requirements

Power	100 kWe
Mass	$<$ 3000 kg
Launch dimensions	STS bay diameter $\times$ 1/3 bay length
Radiation to payload	500 K rad
	7 y at full power
	N—10^{13} nvt

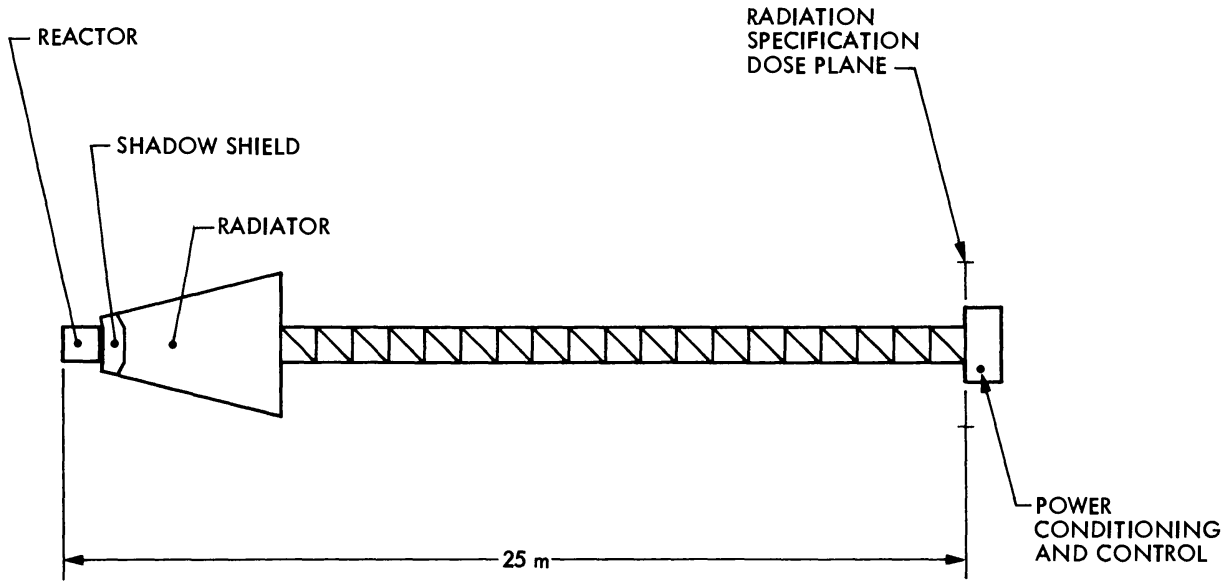

Figure 1. The generic SP-100 design is depicted showing the reactor, shield, conical radiator, and the power conditioning and control unit mounted on a deployable boom at the dose specification plane.

goal is 2 years; however, the design should incorporate no known characteristics that would preclude seven years of full power operation. Launch volume is restricted to the full diameter of the shuttle cargo bay and 1/3 of the length; however, there is no restriction upon deployed size, and variable geometry concepts are viable candidates.

Radiation toward the payload is attenuated by a shadow shield that subtends a solid angle, usually in the 12°-17° half angle range. The radiation levels are specified over a 4.5 m diameter plane 25 m from the opposite end of the reactor (see Fig. 1). Note that this does not mean that the payload must be at 25 m; that is simply the dimension chosen to specify the radiation. The payload may be nearer or more distant as requirements and radiation resistance dictate. The system designers working on the concepts have all chosen to place the power conditioning and control subsystem at the 25 m point. This spacing would be obtained by deployment of an erectable boom structure following deployment from the shuttle but before reactor start-up.

While the values presented in Table 1 are being used as a focus for present design, the SP-100 Project is maintaining awareness of possible need for growth. Power output levels of 100-1000 kWe are possible by allowing mass and volume to exceed the Table 1 limits. Some concepts lend themselves to large growth factors better than others, and selection of growth concepts would depend upon trade-off of a variety of requirements.

SYSTEM CONCEPTS

Three (or possibly four) concepts are presently being evaluated for possible selection. These are listed in Table 2. The first three concepts, usually distinguished by reference to their means of conversion (thermoelectric, thermionic, and Stirling) are presently under

Table 2. System Concepts

Reactor	Heat Conversion	Heat Transfer	Rejection
Fast, compact	thermoelectric	pumped lithium	deployable heat pipe radiator
Fast, thermionic	in-core thermionic	pumped Nak	fixed heat pipe radiator
Fast, compact	Brayton, alternator	pumped Nak	heat pipe or gas, probably deployable

active study by system contractor teams: General Electric, G.A. Technologies/Martin Marietta, and Rockwell, respectively. The fourth concept, the Brayton or gas turbine cycle, was not selected as a prime candidate because of specific technical concerns that appeared to be life- or reliability-limiting in space applications except at the cost of considerable mass. It still appears as a "dark-horse" candidate because of its high efficiency and high level of technical development. In general external appearance, the systems are much the same configuration, differing mainly in radiator size.

The thermoelectric concept, a derivative of the technology used with great success in the Radio-isotope Thermoelectric Generators (RTG) for the Pioneer, Viking, and Voyager spacecraft, offers the advantage of being a static system requiring no moving parts for thermal-to-electric conversion. Materials constraints limit the inlet and outlet temperatures. This, together with the relatively low efficiency of conversion, leads to a large deployable waste heat radiator. The potentially very high reliability and the years of RTG experience are major strong points of this system. The only "moving part" in the entire system is the lithium coolant that is pumped electromagnetically. This carries thermal energy through intermediate heat pipes to the hot side of the thermopiles. The cold side is cooled by the radiator.

The thermionic concept also contains no moving parts, unless the NaK (sodium-potassium eutectic) coolant is so considered. Thermal-to-electric conversion takes place directly in the reactor with the nuclear fuel heating the thermionic emitters and the collectors cooled by NaK. The waste heat from the collectors goes directly to a heat exchanger and then to the radiator. Radiator temperature as well as conversion efficiency is higher than for thermoelectric systems, allowing a smaller radiator. Concern exists as to possible life-limiting mechanisms in the thermionic converters. Inclusion of the conversion capability in the core tends to make the reactor larger and heavier. This may be less significant at higher power levels.

The Stirling system concept involves a free-piston Stirling engine coupled to a linear alternator. This system offers the highest conversion efficiency of any of the concepts, perhaps five times that of the thermoelectric system. The technology is less well-developed than that of the static concepts; however, the high performance and possibility of operating at much lower reactor temperature makes the system of great interest. Areas of concern center about the dynamic nature of the system and the resulting potential for wear and vibration. Efficient means of heat input and withdrawal to and from the multiple engines is an area requiring attention.

The Brayton system, not currently being studied by a contractor, offers efficiency close to that of the Stirling as well as the potential for growth. Concern about life expectancy

resulting from attack of refractory metals by oxygen impurities in the noble gas working fluid as well as the vibration and creep problems inherent in dynamic systems must be dealt with. The system mass may be a problem if waste heat withdrawal must use heat exchange from the gas to a heat pipe radiator. The lighter gas radiator has lifetime/ reliability problems due to micrometeoroids. This system could be a viable candidate for some applications.

APPLICATION OF SP-100 TO A LUNAR BASE

For a variety of reasons, it would be difficult to apply the presently developing SP-100 configuration designs directly to a lunar base. The technology and components developed, however, could certainly be applied to a lunar base power plant.

Problems that might be involved in a lunar surface application are generally due to the presence of the lunar surface. The system is being designed for space use, and proper performance is based upon there being no material in the vicinity except for the system itself and its user spacecraft. Because radiation can be scattered back from surrounding materials, there could be very small changes in criticality for given control settings because of the presence of the lunar surface. This effect should be well within the reactor control capability of SP-100. Radiation will tend to scatter around the shadow shield as well.

The proximity of the lunar surface will detrimentally affect the functioning of the waste heat radiator because of the diminished view factor to space. This will be especially severe during the lunar day when the surface will be itself a heat source in the infra-red range. While all candidate systems will reject heat at temperatures substantially above those of the lunar surface, the effect will generally be such as to dictate larger radiator area. This problem will be less severe if the base is situated at high latitudes.

The lunar environment can be most useful, however, in another role. The shadow shield in the current design only protects a very small area. This would be unsuitable for a manned lunar surface application unless the power plant were to be placed at

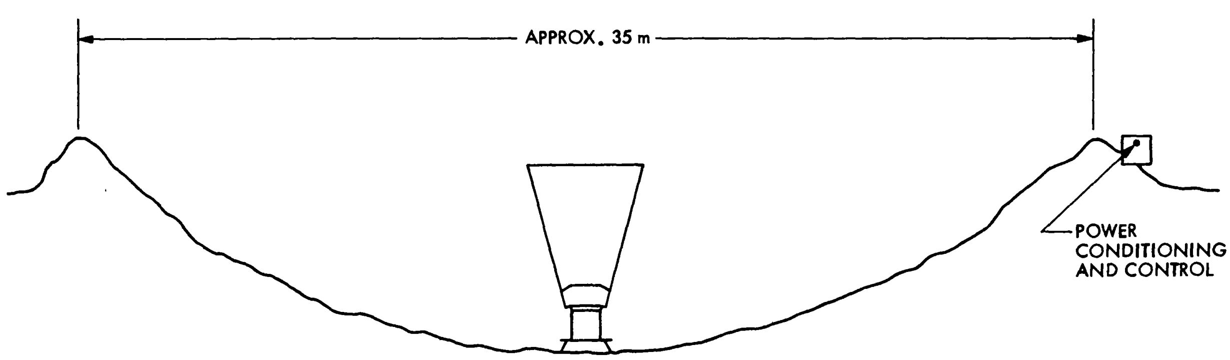

Figure 2. A generic space-type SP-100 mounted in a crater for shielding as often suggested is depicted. Based upon geometry of the Barringer crater in Arizona, a 6.1 m long SP-100 would require an approximate 35 m diameter crater. (Note: Because of scattering, even the radiator must be shielded from manned presence. Thus, unless a large quarantine area is specified, the crater must encompass the complete system.) A longer SP-100, i.e., deployable radiator, would require a still larger crater. Since most heat is rejected from the outside of the cone, the radiator view factor is poor.

a substantial distance from the base (with attendant transmission losses) and approach to it prohibited. Use of lunar materials, as has often been suggested, can solve this problem. While lunar soil or rock is not an especially efficient shielding material, the fact that it is available and "free" (ignoring the effort of collecting it) renders this application very attractive compared with hauling 20,000–30,000 kg of more efficient material from Earth. Whether shielding might be accomplished by placing the reactor at the bottom of a convenient crater or by building up a structure around it needs to be investigated.

The former approach (Fig. 2), if feasible, would certainly be the simpler of the two but may have some inherent disadvantages. For example, in order to provide adequate depth the crater would have to be fairly large. To minimize plumbing lengths for liquid metal, the entire system would have to be within the crater. Once the reactor goes critical, the interior of the crater and, thus, the entire system are off limits. After extensive operations the accumulation of radioactive fission products would preclude close approach even with the reactor off. While it could be argued that this is not important in a system designed for 2–7 years of unattended operations, most individuals with practical experience in operating systems will admit the importance of access for manned inspection and maintenance. An additional problem is reflected radiation from the surface increasing the dose to electronics. The power conditioning and control would have to be outside the crater or specially shielded.

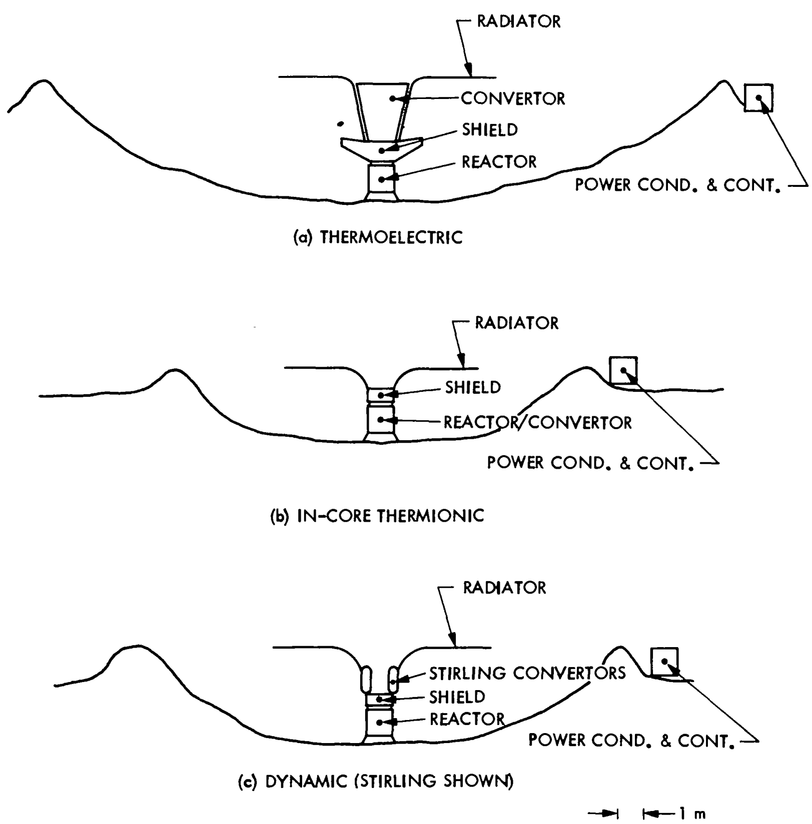

Figure 3. Possible reconfigurations of the SP-100 for use in a crater-shielded installation are shown. In all cases, the radiator is reconfigured as a flat disc rejecting heat mostly from the top side. The thermoelectric concept asssumes that the thermoelectric converter remains a cone shape and that the converter must be shielded from direct reactor radiation and at least part of the ground scatter, hence the large shield. This requires a fairly large crater (say 25 m). If it should not be necessary to shield the converters, they could be configured in a disc as well, resulting in a shorter stack and reducing shield mass. The other concepts are more compact. In the thermionic concept, a shield is assumed only for control electronics, actuators, etc. Similarly, the shield for the Stirling system as shown does not fully shield the Stirling engines and alternators. If this is unacceptable, the shield would have to increase in diameter, but the stack would remain relatively short. (Note: These sketches represent concepts not designs and are presented to show possible options.)

Further inspection of Fig. 2 indicates that this shielding configuration worsens the heat rejection problem by further degrading the view of space. The three parts of Fig. 3 depict conceptually how an SP-100 system might be reconfigured to function up to its full potential in a crater environment. Note that the thermoelectric concept may require a shadow shield to protect the thermoelectric converters.

A custom built shield in combination with a reconfigured SP-100 system is sketched in Fig. 4, showing slightly different configurations for the various conversion concepts. At the cost of slightly longer liquid metal plumbing runs, the conversion systems can be shielded from the reactor allowing for the possibility of maintenance or replacement. Similar comments apply to the radiator.

As previously observed, it is not clear which of the two approaches would be preferred. Certainly the second requires more preparation. They may in fact represent two stages

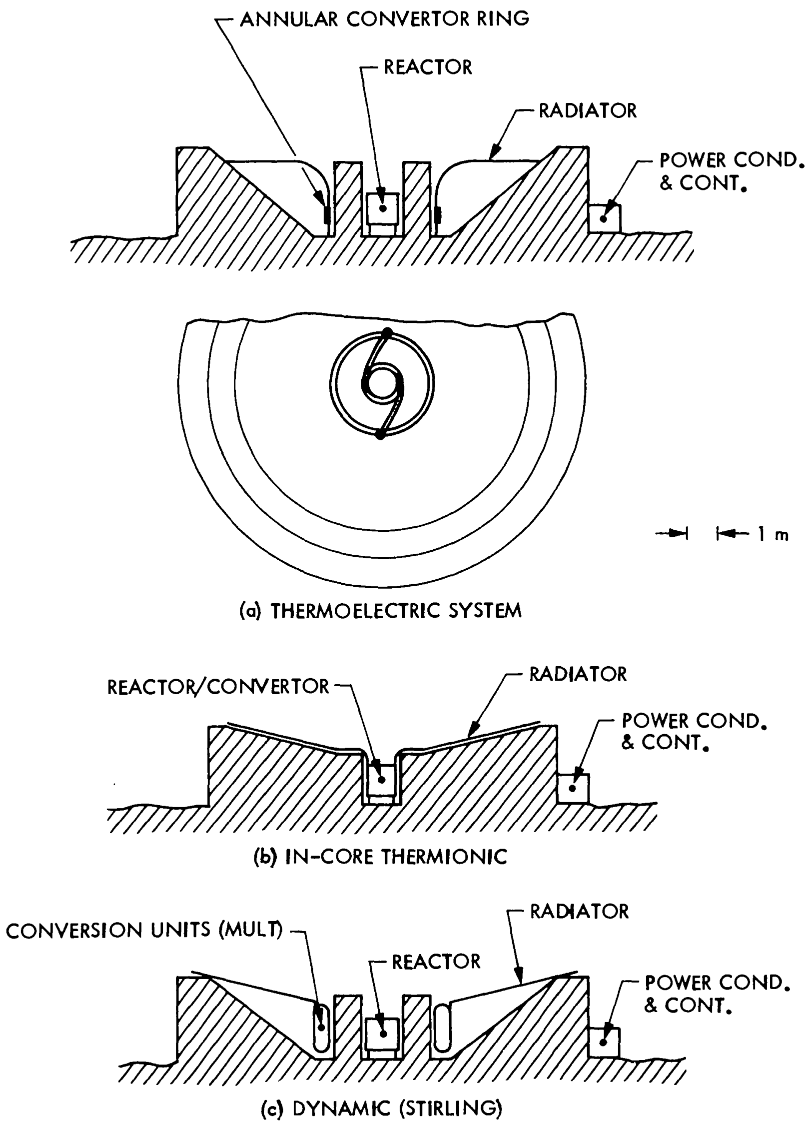

Figure 4. The concepts of Fig. 3 are depicted as reconfigured to operate in a custom shield of lunar material. Such shields might be lunar brick or concrete fabricated by various techniques under study. Most probably, they would be brick or concrete retaining walls filled in with compacted regolith. Since there is relatively little external equipment involved in the thermionic concept, the shield is shown as a solid mass. The other concepts could be similarly configured; however, any attempt to work on the converters would expose personnel to the shut-down but still radioactive reactor. By contrast, the concepts shown in (a) and (c) would allow personnel to enter the cavity for maintenance with the reactor shut-down because of the protection afforded by the inner shield. No shield is shown over the top because it is assumed that control electronics and actuators could be located "around the corner" of the shield. If this is not practical, a small top shield as shown in Fig. 3 (b and c) would be needed.

of evolution, since it seems probable that more than one power plant will ultimately be required for the base.

It is important to remember that the changes to adapt the space version of the SP-100 to lunar surface use are either simply reconfiguration of the major components or relatively minor changes in the components. A complete new development in parallel to SP-100 should not be necessary in order to provide a lunar base power plant.

It seems reasonable to suppose that a 100 kWe nuclear power plant for use on the Moon should not exceed the 3000 kg proposed for the space version. In fact, it might well be considerably lighter since typically the shadow shield mass is 500-700 kg, and this component will probably be unnecessary for some options. The relatively low mass and compact size offer substantial potential advantage compared to solar/storage systems in terms of transportation. Since payload mass and volume will be at a premium, especially during the early years, this consideration should be of substantial importance.

OPERATIONAL CONSIDERATIONS

The obvious advantage of a nuclear power source for a lunar base is the fact that it operates night or day. For a solar-based system, the two-week day/night cycle means either a massive storage system or else shutdown of all but the most vital systems during the night. Even a powered-down lunar base would require substantial power. It has been proposed that solar arrays on high elevations at the lunar poles would always be in the sun. However, even if one wishes to postulate such a construction project, the location of the base will be limited to sites near the poles, which may or may not fit other needs. Nuclear power makes site selection independent of power requirements.

Another advantage is the "waste" heat left over from the conversion process. In the deep space version, this heat is indeed waste, being radiated away to space. For the lunar application in its simplest form, the heat could be radiated to space as shown in the Figs. 3 and 4. This is not necessarily the case, however. The waste (or excess) heat energy might be applied directly to base heating, materials processing, or other functions, thus reducing the need for electrical energy for these applications.

GROWTH POTENTIAL

The excess heat energy might also be used to generate additional electrical energy. It would be possible to couple additional conversion units to accept the excess heat from the primary unit. The in-core thermionic primary system may be best adapted to this purpose, since it rejects heat at the highest temperature of the candidate concepts. A possibility would be coupling one or several Stirling or Brayton units to the system in a "bottoming cycle." These highly efficient units operate at inlet temperatures quite compatible with the heat rejection temperature of a thermionic primary system: about 1000 K. As an example, a thermionic primary system generating 100 kWe would be rejecting an excess of 1000 kWe of thermal energy. If this could be efficiently directed into a Stirling or Brayton system, another 250-350 kWe could be produced. Similar

arrangements are possible with a thermoelectric system; however, the rejection temperature is lower. Substantial waste heat will still be available from the bottoming cycle converters but at substantially lower temperature, say 500–700 K. This will result in much larger radiators. A major advantage of the bottoming cycle approach is that, with proper design, these converters can be added later to an already functioning power system, thus incorporating substitute/power growth potential without requiring a new reactor installation. Coupling of a bottoming system to the primary system might be done by installing some type of coupling plates over the radiators (essentially converting them to heat exchangers). While this approach might not be highly efficient from the heat transfer standpoint, it would avoid the necessity of breaking into the existing plumbing. Alternatively, a heat exchanger and valving could be built into the original system to allow for later integration of the bottoming cycle.

SUMMARY

It appears that SP-100 concepts and technology under development for a deep space system could be readily adapted to provide a lunar base power plant. A nuclear power plant offers substantial advantage because of its compact size and night and day operation. Heat rejected by the primary conversion system may be used for industrial purposes or to generate additional power via a bottoming cycle.

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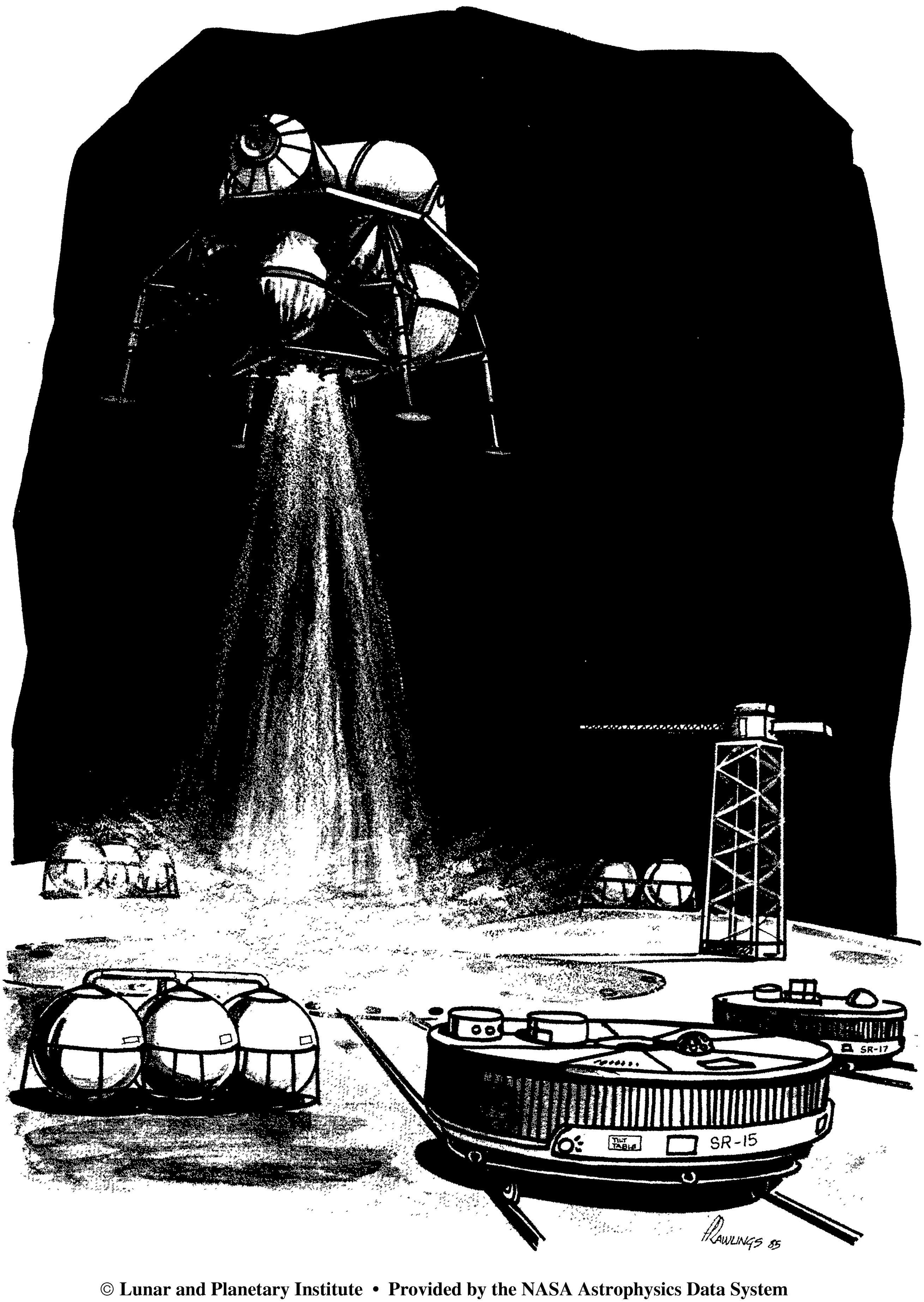
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