THE REAL WORLD AND LUNAR BASE ACTIVATION SCENARIOS

Harrison H. Schmitt

P.O. Box 14338
Albuquerque NM 87191

A lunar base or a network of lunar bases may have highly desirable support functions in a national or international program to explore and settle Mars. In addition, Wittenberg et al. (1986), Kulcinski and Schmitt (1987), and Kulcinski et al. (1988) have reminded us that ^{3}He exported from the Moon could be the basis for providing much of the energy needs of humankind in the twenty-first century. Both technical and managerial issues must be addressed when considering the establishment of a lunar base that can serve the needs of human civilization in space. Many of the technical issues become evident in the consideration of hypothetical scenarios for the activation of a network of lunar bases. Specific and realistic assumptions must be made about the conduct of various types of activities in addition to the general assumptions given above. These activities include landings, crew consumables, power production, crew selection, risk management, habitation, science station placement, base planning, science, agriculture, resource evaluation, readaptation, plant activation and test, storage module landings, resource transport module landings, integrated operations, maintenance, Base II activation, and management. The development of scenarios for the activation of a lunar base or network of bases will require close attention to the "real world" of space operations. That world is defined by the natural environment, available technology, realistic objectives, and common sense.

INTRODUCTION

A lunar base or a network of lunar bases may have highly desirable support functions in a national or international program to explore and settle Mars. As yet, such bases probably cannot be shown to be absolutely necessary in such a program. However, the Moon's resources, its reduced gravity, and its proximity to the Earth as a proving ground for planetary settlement technology should not be ignored in the analysis and planning of such an endeavor. The Moon probably could serve as a means of reducing the complexity, the cost, and the risk of implementation of any long-term commitment to Mars.

In addition, *Wittenberg et al.* (1986), *Kulcinski and Schmitt* (1987), and *Kulcinski et al.* (1988) have reminded us that ^{3}He exported from the Moon could be the basis for providing much of the energy needs of humankind in the twenty-first century. Deuterium/helium-3 or "Astrofuel" (*University of Wisconsin,* 1988) fusion has numerous advantages over more conventional fusion and fission cycles, and may become the basis for providing large amounts of continuously available electrical power in space as well as on Earth. The by-products of Astrofuel production on the Moon also have the potential for making lunar bases into totally self-sufficient settlements.

Both technical and managerial issues must be addressed when considering the establishment of a lunar base that can serve the needs of human civilization in space. Many of the technical issues become evident in the consideration of hypothetical scenarios for the activation of a network of lunar bases.

The purpose of hypothetical timelines or scenarios is to begin that long and interesting process of bringing realism into the modeling of future mission requirements, in this case, the creation, operation, and maintenance of a network of productive bases on the Moon. It is a first step toward the development of a "Design Reference Mission" that can serve as the basis for developing engineering designs, consumables budgeting, launch support requirements, flight operations procedures, economic analyses, and management structures.

A detailed scenario delivered to NASA as part of a report by System Development Corporation (*Schmitt,* 1986a) portrays the major day-to-day activities related to the first two years in one scheme for the establishment, initial operation, and maintenance of a lunar base network. The explanations of the logic underlying this scenario were extracted and slightly revised for this paper.

The general assumptions underlying this particular scheme are as follows.

1. The principal functions and justifications for the lunar base network, aside from those related to nation building and international policy issues, are (a) the production of oxygen in the near term and ^{3}He in the long term for use in support of other space and Earth activities and (b) the continued scientific exploration and utilization of the Moon.

Lunar-produced materials for use in space have the basic advantage over terrestrially produced materials of lower export costs from a gravity environment only one-sixth that of the Earth. Further, ^{3}He or Astrofuel is a potentially very attractive fuel for fusion power that has a very limited availability on Earth but for which there is a large resource base on the Moon (*Kulcinski and Schmitt,* 1987). The production of Astrofuel on the Moon can give by-products to support self-sufficient lunar settlements.

Potential scientific activities on the Moon include support of lunar resource development, further extrapolation of the Moon's special planetological relationships to the Earth, Mars, Mercury, and Venus, and use of the unique advantages of the Moon's farside as a platform for astronomical observations.

2. The frequency of major spacecraft landings on the Moon in support of the activation of the first lunar bases will be one per lunar cycle. Although higher or lower landing frequencies, and thus frequencies of major launches from Earth or space stations,

can be accommodated, a frequency of one per lunar cycle appears to give a good balance between the following: (a) additional burdens on launch operations on Earth; (b) optimum sun angle for crew landings; (c) operational and safety implications of missing one scheduled landing with crews on the Moon; and (d) gradual escalation of long-duration exposure of humans to a reduced gravity environment. Landings on the Moon at a rate of one per lunar cycle also can support the activation of a second base provided that launch and spacecraft capabilities can support a step increase (possibly about 50%) in payload weight landed on the Moon per landing. The lunar landing frequency required to support the activation of a third base has not been examined, but it is likely that either a higher landing frequency or another major increase in payload weight landed per landing will be required unless it becomes possible to bootstrap additional bases from the first two.

3. Engineering designs for the major support systems for a lunar base network will be finalized prior to initiation of the activation of the first base. These support systems include landing modules (LMs), habitation modules (HMs), lunar roving vehicles (LRVs), power plants (PPs), regolith mining plants (RMs), oxygen prodution plants (OPs), Astrofuel production plants (APPs), agricultural plants (APs), storage modules (SMs), and resource transport modules (RTMs). On the other hand, it is likely that the operational testing of prototype equipment at the first base will disclose needed modifications. Thus, the original designs must include characteristics that will rapidly accommodate such modifications.

4. The site for the first base of the network will be selected as that which is best for the operational testing of all basic support systems as well as being suitable for resource production. The mineral ilmenite (Fe_2TiO_4) probably will be the raw material for oxygen production (*Williams and Erstfeld,* 1979). Ilmenite-rich regolith also appears to be most favorable for Astrofuel production (*Cameron,* 1988). It would be highly desirable to take advantage of our existing knowledge about ilmenite abundances related to an Apollo landing site. Solely from this perspective, either areas geologically related to the Apollo 11 Tranquillity Base or Apollo 17 Taurus-Littrow sites appear to be the best candidates for Base I because of the high abundances of ilmenite in their soils (*Taylor,* 1982). Science considerations would probably favor the Taurus-Littrow area, whereas the ease of operational access and total resources available would appear to favor areas north of Tranquillity Base.

5. The site for the second base will be selected as that which is best for sustained resource production if demand warrants. It may be that confidence gained from remote sensing of ilmenite-rich areas other than Taurus-Littrow and Tranquillity Base will permit selection of a Base II site that lies in the western region of the Moon. This would be very desirable from a scientific point of view, as would be a third base location on the lunar farside, such as in the large crater Tsiolkovskiy.

6. The lunar tour of duty for crews will be roughly 3 lunar cycles for the first year, 6 lunar cycles for the second year, and 12 lunar cycles for the third and subsequent years. Longer tours of duty or even permanent residence probably can be accommodated with a concurrent reduction in launch support requirements. However, it seems prudent to build up gradually from the Skylab, Salut, Mir, and space station experience with human adaptation and readaptation in reduced gravity environments.

7. The crew work cycle during base activation and operation normally will be 10-hour days and 6-day weeks. The Apollo experience indicates that this workload is easily sustainable in one-sixth gravity provided the long-standing problems in leg mobility and in the design and operation of pressure suit gloves are eliminated. At times, it may be difficult to resist longer hours and seven-day weeks if hardware permits.

Specific and realistic assumptions must be made about the conduct of various types of activities in addition to the general assumptions given above. Examples of such activities and the assumptions that might be made about them are given below.

Mission rules. Scenarios for the activation of a lunar base should include consideration of likely "mission rules," that is, ultimately nonnegotiable requirements related to crew safety. For example, the status of crew return modules would be checked prior to proceeding with a landing or a departure that might isolate a crew on the Moon if one of the return modules were inoperative. The establishment of mission rules is a continuously iterative process and may impact the overall scenario at any time.

Landings. The first landing at a base site (Day -28) is an automated or remotely guided placement of an HM keyed to a precisely determined and nonhazardous point on the surface and to the plan for the final architecture of the base. Twenty-eight days later (Day 0) the first crew lands manually, keyed to the previously landed HM and to the base plan. Sufficient reserves of propellants must be on hand for both initial landings to maximize the probability of success. Subsequently, both automated and crew landings can be made precisely to landing beacons on local sites selected or prepared by preceding crews. This will reduce the propellant reserves required for landing and consequently increase landed payload capability.

Crew consumables. The basic philosophy behind crew consumables supply is to have sufficient margins to maintain normal consumption if the next scheduled resupply mission did not take place. Mission rules and common sense will require that the crew begin to conserve consumables if a scheduled resupply were indeed missed. Consumables (water, food, oxygen, and nitrogen) that would eventually be produced at the base would ultimately begin to significatnly reduce landed consumables requirements.

Power production. Power production and storage for the base is obtained in two stages. First, relatively small power plants and power storage systems are included as modules with the landings of the habitation modules (Days -28 and 29). The first crew lands with a backup power module and power storage system (Day 0). These systems must provide power for both day and night operations and habitation. If solar cell and battery systems are used, it is likely that sun tracking solar arrays will be required so that excess power can be generated during the lunar day for battery charging. If fuel cells are used, or a combination of solar cells and fuel cells, then cryogenics for the fuel cells must be resupplied from Earth at least until oxygen and hydrogen are in production at the base. As in the case of crew consumables, it is planned to have margins for power consumables sufficient to maintain normal base operation through at least one missed resupply opportunity.

The second-stage power production and storage systems must be sized to provide the power necessary for continuous operation of the fully operational base. It would appear that both first- and second-stage power systems, even if they use nuclear heat sources, should include fuel cells. This would enable the base to efficiently use lunar oxygen and hydrogen for the production of water, with electricity as a by-product, and thus avoid dependence on the costly import of water.

Should fuel cells become a major component of base power systems and should their maintenance require replenishment of significant electrolytes containing Na, K, Cl, or F, the cost of resupply of these elements vs. the cost of lunar production should be examined. Lunar orange and green soils and KREEP basalts are potential sources of these elements (*Schmitt*, 1986b).

Crew selection. Crew selection and training leading up to full activation of a base will be governed largely by the specialized activities each crew will be required to perform. An appropriate payload specialist will be on each of the crews through full activiation, whereas subsequent crews responsible for base operation may be more generally trained. Once the upgraded landers are available for Base II activities, additional scientific specialists should be accommodated as permanent personnel at the bases. Habitation module designs should take into consideration this possibility of step increases in the numbers of base personnel.

Health maintenance considerations will make it highly desirable to have a trained physician as a payload specialist at each base at least by the time six persons are in continuous presence. Such physicians also will be required to fulfill a full range of other base responsibilities, as will the scientific payload specialists present throughout the base activation period.

Risk management. The activation of lunar bases will require some new attitudes as well as new approaches toward risk management. For example, once crews are continously active on the Moon, there cannot be a long-term stand-down in the use of the transportation system (as had been the situation with the space shuttle) on which base activities and, indeed, crew survival may depend. Confidence in the tranporation systems must be such that they can be used even in the face of an accident or unforeseen design deficiency. Further, a severely injured or ill person on the Moon must be treated there. Otherwise, the activation or operation of a base will be seriously compromised. Contingency plans should be aimed more toward quickly adding personnel to a base having a personnel problem rather than quickly returning a person or crew back to Earth.

Equipment design must include "fail-safe" philosopies as well as the capability to repair and upgrade rather than discard. Major external risks from the environment, such as solar flares, must be managed by initial habitation design and by easily implemented procedures should the crew be caught in an exposed situation during a flare. In this case, appropriate shielding materials and other design considerations should be incorporated into LRVs so that they can form the roof of an explosively excavated trench (*Dick et al.*, 1986).

Habitation. The delivery, check-out, inspection and maintenance, and upgrading of habitation modules are sequenced so that sufficient capability is available at all times and the lifetimes of modules are maximized. As the modules will need to be covered by 2-3 m of lunar soil for protection from solar flares and cosmic rays, it is anticipated that trenches will be excavated in the regolith next to the lander that delivered each module. In turn, this requires that the lander design both protect the modules from the effects of excavation and provide for off-loading and placement of the module in its trench. The LRV or other device must then have the capability to move nearby regolith over the module and cover it to the required depth.

The Apollo experience indicates that a "dust lock" (in contrast to an airlock) will be a mandatory component of the habitation module. Although the absence of lunar atmosphere prevents the billowing and air transportation of lunar dust outside the habitats, the crews will carry dust on their pressure suits through the entrances to the modules. The highly penetrating and highly abrasive character of this dust makes it a very undesirable addition to the module's interior environment.

Although the scenario provides for the upgrading of the habitation modules to accommodate continuous rather than discontinuous use (two lunar cycles on, one lunar cycle off), major upgrading may not be necessary depending on the initial design. However, it is likely that the joining together of new module components as a base develops will be desired as well as the addition of unanticipated new capabilities. Thus, the module design should include built-in interfaces for upgrades.

Science station placement. Each lunar base will certainly be a major scientific observatory for lunar, solar system, and astronomical phenomena. The base plan should therefore include an appropriately selected site for one or more scientific stations. The timeline provides for the deployment and activation (Day 10) and the regular inspection, maintenance, and upgrading of the base's scientific systems.

The location of sites that constitute the lunar base network will greatly affect the value of each site's scientific station. If the Mare Tranquillitatis were selected for Base I, then a western ilmenite-rich site for Base II and a farside southern hemisphere site for Base III would make good sense. Depending on the demand for lunar resources, Base III might well be a purely scientific site, particularly one that could take advantage of the unique astronomical "viewing" potential of the lunar farside.

Base planning. The layout and architecture of the core of each lunar base must be planned in detail prior to any landing or activation activity. The automated landing of the first HM and all subsequent landings should conform to these plans. The first crew must insure that the plan is not only feasible, but can conform to the realities of the selected site.

Some of the considerations for the planning process are as follows:

1. Proper location of all landers relative to the site of the resource production plants so that they can be used later either to store produced resources or their by-products or to be refueled and reused.

2. Proper location of the landers bringing RTMs so that the RTM launch area is appropriately spaced relative to the production plants and other facilities.

3. Proper location of the entire base relative to its resource base in order to maximize the efficiency of extraction, beneficiation, and transport of concentrates to the resource production plants.

4. Proper location of the scientific station and agricultural plant enclosure so that they are unaffected by base activities that create dust, gas, seismic noise, and high-velocity particles that could damage these facilities or adversely affect their performance.

Science. Subsequent to the initial scientific survey of the base area and prior to the activities leading up to full activation of resource production, general scientific activities dovetail well with the overlap of crews on three-lunar-cycle tours of duty. The activities contemplated are those that extend scientific knowledge of the Moon, deploy geophysical and astronomical sensors, and define potential resources accessible to the base.

Once there is preoccupation with the activities of resource production, extensive scientific investigation will require the landing of extra payload specialists or entire crews for this purpose. Such augmentation of the scientific activities at a base requires not only additional habitation capacity, but also more frequent landings than assumed for this scenario or the provision for permanent residents. One other alternative that could increase time available for scientific activities is successful automation of other base operations once systems are activated. Time will tell whether this proves to be practical.

Agriculture. The initiation of the investigation of food production on the Moon and the later activation of an agricultural plant are related both to the need to minimize imports of food and to the need to dispose of biological waste through recycling. The agricultural experiments and facilities will probably include a large inflatable and pressurized greenhouse and may require a self-contained fuel cell power system to provide water and lunar night lighting for photosynthesis. Radiation sensitivity of some lunar crops may require regolith shielding on the greenhouses, combined with the use of light pipes during the lunar day. Ultimately, food produced on the Moon may become a significant commodity for export to space stations.

Resource evaluation. As resource production is one of the main functions of a lunar base network, the early and detailed delineation of ore grades is essential to the long-term operation of each production center. The evaluation of the distribution of ilmenite-rich and ilmenite-poor zones within the regolith, as well as the concentration of adsorbed solar wind gases, will be an ongoing process. Such evaluations will be essential to the development and implementation of a mine plan.

Although ilmenite probably is evenly distributed in individual ilmenite-rich basaltic lavas from which most local regolith is derived, it is also clear that ilmenite-poor zones will be present as a consequence of the deposition of layers of pyroclastic materials, avalanche debris, and impact debris fron nonlocal sources. Surface mapping, the interpretation of local geological features, and the grid-controlled analysis of bore hole samples will be required to adequately delineate the ilmenite-rich ore zones to be mined and the ilmenite-poor waste zones to be discarded or avoided.

It probably will be desirable to equip the LRVs with semi-automated or automated boring, sampling, and analysis systems in order to minimize the time required for resource evaluation.

The actual mining of the regolith will be conceptually similar to large-scale dredging operations such as used to mine rutile from placer deposits. The regolith mining plant (see *Sviatoslavsky and Jacobs,* 1988) will need to be mobile, with self-contained primary and secondary resource concentration systems and grade monitoring systems. This will minimize the quantity of bulk material transported to the production plants and provide the capability for close control of the ore grade being mined. The regolith mining plant must be capable of detecting and avoiding or removing obstacles to mining such as large boulders.

Readaptation. Although one-sixth gravity probably has significantly less adaptive effects on human physiology than does total weightlessness, it is likely that some activities related to a crew's eventual readaptation to Earth's gravity will be desirable. The protocol for these activities is initiated about two weeks before a crew's return to Earth. The protocol will probably include activities that gradually increase skeletal and cardiovascular stress over this period. By the time we begin to activate a lunar base network, space shuttle and space station research should have defined prophylactic measures against adaptive deterioration.

Plant activation and test. The activation and test of the power plant, the regolith mining plant, and the resource production plants are critical not only to future integration of base operations, but also to verifying designs. If design flaws are discovered during these activities, it is essential that overall designs permit correction of such flaws rapidly and at the base.

Storage module placement. With lengthened tours of duty and less frequent landings at Base I as Base II is initiated, it will be necessary to bring into service SMs that can not only provide for the landing and storage of consumables, but can deliver empty resource transport modules to the base. These SMs will probably require use of the step increase in landed payload capability that also will be needed as Base II is activated.

Resource transport module placement. The regular supply of oxygen, Astrofuel, and any other resources from the Moon implies the existence and regular delivery of empty RTMs to each production base once operational production is initiated. The scenario provides for these activities through the cycling of four and eventually five RTMs to and from each base. It appears that, with the assumptions made to develop this scenario, each base might launch a loaded RTM every two lunar cycles. With launches staggered, this means that a lunar oxygen, and perhaps fresh food, delivery to a space station can be made every 28 days with two operating production bases. However, because landings at each established base in a three-base network will occur at an average frequency of less than one every two lunar cycles, it will occasionally be necessary to return empty RTMs to the base in pairs.

Integrated operations. With the landing of the sixth crew and its planned six-month stay, the stage is set for a build-up to integrated operations. Initially, the sixth crew integrates regolith mining and resource production while the fifth crew integrates resource and by-product production with storage in old landers and/or RTMs.

In order to undertake the full integration of these systems as well as other necessary base functions, it probably will be necessary for the fifth and sixth crews to split into two-person shifts. It appears that this practice will be necessary indefinitely unless a high level of automation and systems reliability is possible or larger numbers of personnel are available.

Maintenance. Throughout the activation of a base, attention is given to inspection and maintenance of base facilities and plants. Once the base is in full and continuous operation, it is likely that one of the two-person shifts will be an inspection and maintenance shift. This shift will have to work its way through all base systems on a regular cycle. A capability for repair, replacement, and spares delivery must be clearly defined and implemented if base functions are to be maintained continuously. Further, inventory control of all discarded materials and parts should be maintained in case they might be of some unanticipated future use.

Base II activities. It is anticipated that the activation of a second base for resource production would follow the same general scheme as that for the first base except for the following modifications: (1) landings would be less frequent; (2) crew tours of duty would be longer and crew responsibilities more varied; and (3) landed payloads would be larger.

Management. Most of the technical and operational management of an operating lunar base network must be contained within the network itself. However, logistics coordination with space stations and Earth will be essential, first, to insure a successful activation of the network and, second, to properly phase exports, imports, and crew replacement. Thus, it would appear that, at least for the first few years, overall network activities must be coordinated from Earth, but the individual bases must be capable of significant and ever-increasing operational autonomy.

CONCLUSION

The development of scenarios for the activation of a lunar base or network of bases will require close attention to the "real world" of space operations. That world is defined by the natural environment, available technology, realistic objectives, and common sense.

The natural environment must be understood, and Apollo and Earth orbital flights have given us much such understanding. Available technology is under our control, and it can be expanded to meet the objectives of the base. Realistic objectives come with vision, but they must be reevaluated and refined continually.

Finally, common sense in space comes with experience and the interplay of ideas. No one has a monopoly on common sense, but the synergistic interaction of many professionals will go a long way to providing all that is necessary. We have done it before. Let's do it again.

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