

# **Symposium on**

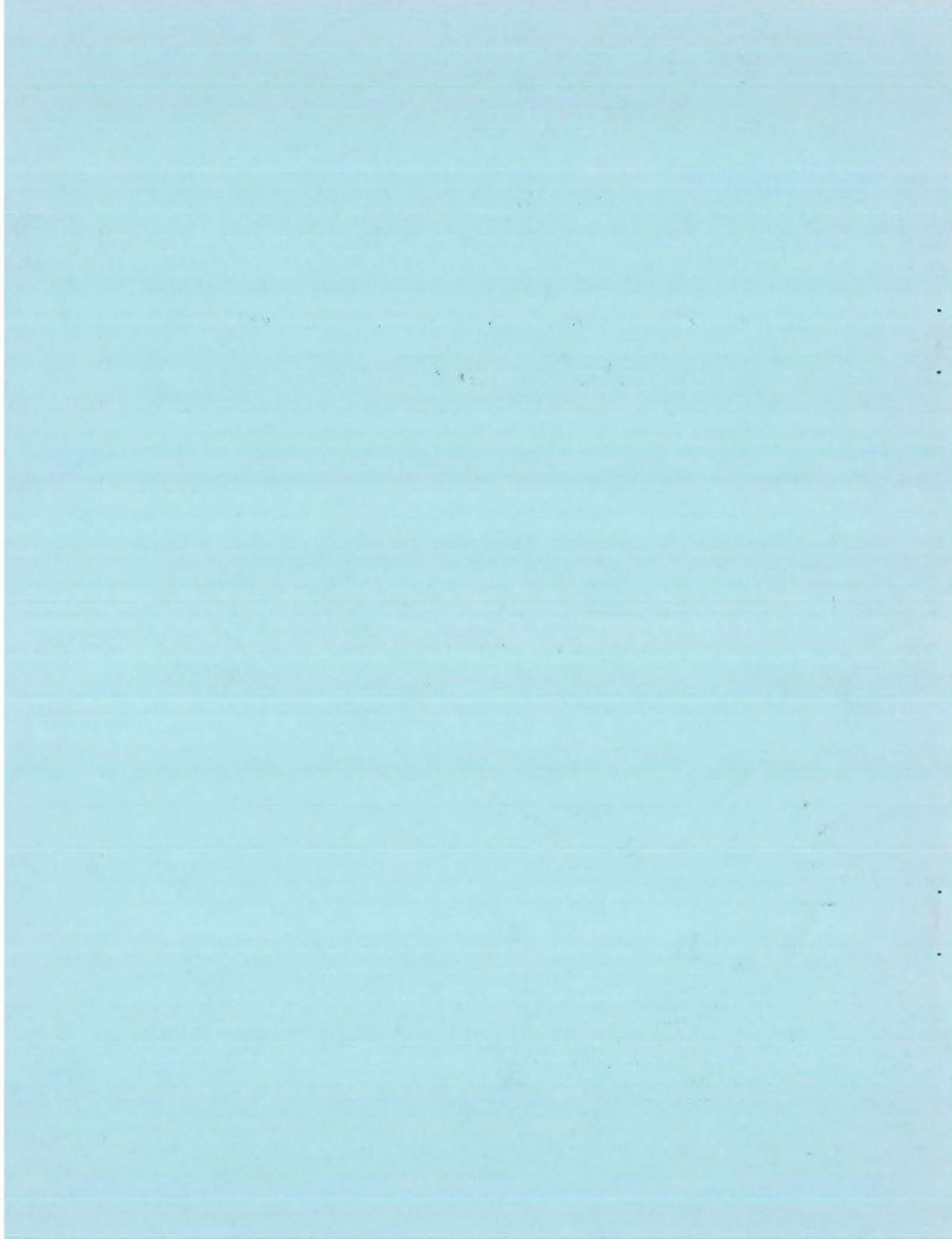
## **Lunar Bases and Space Activities of the 21st Century**

**APRIL 5 - 7, 1988  
HOUSTON, TEXAS**



**Sponsored by:**

National Aeronautics and Space Administration  
American Institute of Aeronautics and Astronautics  
Lunar and Planetary Institute  
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National Space Society





Papers Presented to the  
**SYMPOSIUM ON LUNAR BASES AND SPACE ACTIVITIES IN THE 21ST CENTURY**

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## PREFACE

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**BLUEPRINT FOR ACTION: Establishing Political Support for Lunar Bases.**  
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While Mars Missions, jointly with the Soviets, manned and unmanned, have gained political currency with the current Administration and 1988 Presidential candidates, the Lunar Base concept has gained support from NASA, or at least parts of NASA, and the National Space Society. While Carl Sagan has called the Moon boring, Isaac Asimov has called for an evolutionary approach to Mars via Moon bases and the Space Station. Why is the romance of the Red Planet overshadowing support for the development of economic infrastructure and technical know-how to be provided by the establishment of Lunar Bases and Space Stations, and thereby assuring the long-term success of permanent occupancy of not only Mars, but of other parts of our solar system as well?

Political support for Lunar Bases is narrow and deep but without an identifiable public advocate, while support for Mars is broad but shallow and led by the public figure, astronomer Carl Sagan. In politics, all is perception and image. And, unfortunately, the current Administration perceives that the U.S. public supports Mars Missions and not her less glamorous counterparts. That is because no equivalent Carl Sagan-type figure has come forward to press the case for Lunar Bases and Space Stations. Sagan has used his organization, the Planetary Society, in support of Mars Observer (MO) program -- Congress was inundated with letters in support of the MO program in the 1988 Fiscal Year budget cycle.

The much smaller National Space Society, a merger of the L5 Society (space colony advocates) and the National Space Institute (NASA program advocates), has fought long and hard for the Space Station as a near-term goal for the building up of space infrastructure that will insure space industrialization and commercialization as part of an overall scheme which includes Lunar Bases as a means for insuring the economic viability of manned Mars Missions and permanent occupancy by mankind of our solar system.

The success of Sagan supporters can be explained by their proactive activities. Unfettered by the mundane work of fighting for the Space Station (until recently, Sagan fought against the Space Station . . . now he says it's good for only one thing -- building vehicles that would be launched from there to go to Mars). Sagan has also used the hopes for a better future and a more peaceful world by appealing for support of joint U.S./U.S.S.R. missions to Mars. The cost of the missions that he has proposed is enormous and if undertaken should establish permanent outposts for mankind on other planets and not just be one-shot missions.

To sell the cause of Lunar Bases will take more than logic and scientific rhetoric. What is called for is a public relations campaign which recognizes the big guns which have been used by Sagan; peace and romance are very sexy . . . mining for Lunar oxygen and ores is not romantic, it is plain, hard, dirty work. The question becomes, how does one sell a plan for the building of an infrastructure which will make it possible for more than a select few human beings (maybe a half dozen) to go to Mars and return safely within the next thirty years? What about a plan which will allow anyone with the funds and health to make the trip themselves within the next fifty years? Our society makes those economic decisions for future generations every day, can we ill afford not to make the long-term investments which will insure that not everyone living off the planet in the next century will speak Russian (or Japanese or French or Chinese)?

How should such a campaign be organized? Who should lead it? Where is the public spokesperson needed to represent Lunar Bases? At what level should and can the scientific community and the advocacy community coordinate and interact? How can existing mechanisms and organizations be tapped to efficiently and successfully support the political basis for funding Lunar Bases? In whose interests are Lunar Bases?

A blueprint for action requires that all available resources be activated. This paper examines those resources and presents a plan for the strategy and tactics to successfully sell the building of space infrastructure into the next century.

This abstract withdrawn by author.



## PROPULSION FUELS FROM INDIGENOUS LUNAR AND ASTEROIDAL METALS

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Lunar and asteroidal surface materials are ubiquitous and abundant sources of metals like silicon, aluminum, magnesium, iron, calcium, and titanium. Many schemes (1,2,3) have been proposed for extracting these metals and oxygen for structural, electrical, and materials processing space operations. However, all the metals burn energetically in oxygen and could serve as in-situ rocket fuels for space transportation applications.

Table 1 lists the specific heats of combustion (enthalpy) at 1800 K and corresponding specific impulses at selected mixture ratios with oxygen of the above pure metals assuming rocket combustion at 1000 psia and an expansion ratio of 50. Hydrogen is included for comparison.

Table 1: Metal/Oxygen Combustion Properties

<u>Metal</u>	<u>Specific Enthalpy (Joules/kg)</u>	<u>Isp (seconds)</u>
hydrogen	$1.39 \times 10^7$	457
aluminum	$1.63 \times 10^7$	270
calcium	$1.41 \times 10^7$	213
iron	$4.7 \times 10^6$	184
magnesium	$1.83 \times 10^7$	260
silicon	$1.58 \times 10^7$	272
titanium	$1.17 \times 10^7$	255

All the metals appear to offer adequate propulsion performance from low or moderate gravity bodies and are far more abundant than hydrogen on many terrestrial planets and asteroids. It is noteworthy that silicon, the most abundant nonterrestrial metal, is potentially one of the best performers. In addition, iron with the lowest specific impulse is sufficiently energetic for cislunar and asteroidal transportation. Further, silicon and iron are the most readily obtained nonterrestrial metals. They can be separated by distillation of basalts and other nonterrestrial silicates in vacuum solar furnaces (3).

Efficient rocket combustion of metal fuels could be realized by injecting them as a fine powder into the combustion chamber. This could be done by mixing the fuel with an inert carrier gas or in liquid oxygen (LOX) to form a slurry. Preliminary studies indicate that a mixture of metal/LOX can be stored and handled safely without danger of autoignition. Lean fuel mixtures would be used to achieve the maximum specific impulse by reducing the exhaust molecular weight without excessively lowering the combustion temperature. Two phase flow losses are estimated to be acceptable for anticipated throat sizes based on measured thrust loss data from solid rocket motors using aluminized propellants.

The metals could be atomized by condensing droplets in vacuum from a liquid metal stream forced through a fine ceramic nozzle. Brittle metals like silicon and calcium might be pulverized to sub 20 micrometer size in vacuum in autogenous grinders that operate by centrifugal impact and are independent of the gravity level.

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### UNIVERSAL CLAMPING SYSTEM

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Storage structures on Earth are required to counter gravitational forces as well as provide rigidity and stability. The microgravity conditions of space presents unique challenges since the storage compartment must secure and contain items to prevent floating objects from causing injury to crewmembers, vehicular structures, or to other pieces of hardware. The weight and volume limitations for orbiting space vehicles mandate that structural storage items be lightweight, compact, adaptable, and easily configured to perform multiple operations. This paper presents the concept of a structure system which secures items by clamping mechanisms. These clamping mechanisms provide mechanical strength and stability, are reliable and easily operated and repaired as well as meet the requirements for safety and materials for use in a space vehicle.

The advantages of the Universal Clamp System (UCS) involve its ability to be used within a wide range of applications. The UCS is composed of interconnecting components which may be easily hand-assembled to provide fastening, positioning, and clamping capabilities. Because the structure built from the clamping system may be of any dimension, the need for numerous sizes of components is eliminated, representing a savings in design and development time, and possible stowage volume. The use of tools for assembly is eliminated, reducing difficulties associated with screws and other small pieces which can float through the space vehicle. Dependent upon final design specifications, it is expected that compact stowage can be achieved. It is also expected that, with certain modifications to the design for use in flight, the Universal Clamp System may be used on Earth for many common applications.

Basic components of the UCS set are:

- Straight connecting rods for transmission of torque and axial stress and structural support of equipment items.
- Octagonally shaped connecting pieces or joints for intersection of two or more rods.
- Modified connecting (end) pieces which contain a screw-type modification within the configuration of an ordinary connecting rod, to induce tension or compression within the assembled clamp. When the system is used to hold objects together, the tension piece will allow tightening or loosening of the entire configuration.

The UCS operates by application of stresses through a series of cantilever rods which are held together by frictional forces at connecting joints. Linkage is obtained by press-fitting rods into sockets contained within other rods, or in special linkage components. In applications where tightening of the configuration against specific items of hardware is desired, insertion of a tensioning rod, consisting of two separate rods, each threaded at one end and joined within a turnbuckle, can be effected in order to generate necessary stresses within the component pieces. Fixation of the UCS is possible by a number of methods dependent upon application and desired action. If pegboards are supplied in spacecraft workbench areas, connecting rods may be press fit into walls in order to provide structural support for containment purposes. Suction cups and vacuum vise grips may be provided to provide attachment in areas where smooth surfaces predominate.

The UCS is unique in its simplicity and ability to be configured to meet the requirements of numerous situations involving clamping, fixation, and containment. The UCS may be applied to items of all sizes, and as geometry and other constraints require, the structure of the clamp system can be modified as necessary.

MAN THE CRITICAL ELEMENT: Chapter II  
A Lunar Colony from a Behavioral Scientist Point of View

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If we go to the moon looking for profit or more scientific facts about our universe whose going to take care of forming the new civilization and what form should we use? Our mission to build a colony on the moon is more than a scientific experiment - more than just an exploration. This will be the beginning of a new world much as the U.S. Jamestown Colony was in 1607 only there aren't going to be any Indians to help us through the first cold winter.

The National Commission on Space has stated that new research should be undertaken in the subjects of gravity, radiation exposure, environmental toxicology, nutrition as it affects performance, microbial environment, epidemiology, functioning of the body's defense mechanisms and dynamics of inter personal interactions in a closed environment. In my first paper on "Man the Critical Element", I discussed how the individual could best cope with living in such a foreign environment referring to several of the subjects the Space Commission noted above. The second paper will begin where the first paper ended. Now, the individual having put together the best possible circumstances he can for himself with the variables available, how can he then gain additional resources to lend to his creativity, his energy level, his harmony, his well being from the other individuals in the group? How can he lend his own resources to the group to increase in these same areas for other individuals?

How can we coordinate a winning team from super great individuals who perform their task well? What makes a winning team anyway? Research shows us that individuals who compete for positions rarely make a good cohesive team. Groups with certain elements will always win, outlast, and survive other groups. What are these elements? I will talk about these and the basic needs of a new civilization as I see it.

DEVELOPMENT OF A MANNED LUNAR OUTPOST: YEAR 2000-2005

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The Lunar Base Program is a bold, new U. S. Space initiative to establish a self-sufficient lunar facility providing for permanent human habitation, intensive science, and export of lunar materials for use in space. To assist with the development of this initiative, the Advanced Programs Office of the Johnson Space Center has assembled a NASA-sponsored study of the Lunar Base that draws on the resources of JSC, other NASA centers, national laboratories, and the university community. This study is called the Lunar Base Systems Study (LBSS). The LBSS has created an engineered scenario for a manned lunar outpost, beginning in the year 2000 and ending in the year 2005. The results are both a "yardstick" by which other lunar base scenarios may be compared and a repository of pedigreed information that can be used to "flesh out" other lunar base options.

The primary site selected for the study is Lacus Verus (87.5W,13S), a limb site near Orientale with farside access. However, three other sites are to be considered in the LBSS in order to determine sensitivities. These sites are Apollo 17, the South Pole, and Mare Nubium. Three assumed strategies are being pursued; Habitation as soon as possible, Science as soon as possible, and the Civil Needs Data Base, Option III (July 1987) strategy. In addition to a strong science aspect in each of the strategies, the LBSS is stressing the development of local resources. The products of the Lunar Base Systems Study will be available in a NASA Technical Publication in October 1988.



**RADIATION PROTECTION ISSUES AND TECHNIQUES IN SUPPORT OF LUNAR BASE OPERATIONS.** Joseph A. Angelo, Jr., EG&G, Inc. 100 Eyster Blvd, Rockledge, FL 32955; Richard G. Madonna, Grumman Corporate Research Center, Bethpage, New York 11714; William Quam, EG&G Santa Barbara Operations Group, Goleta, CA 93117

Long-term exposure to ionizing radiations, even at presumably "low levels", could have harmful effects on human beings and sophisticated electronic equipment. The natural radiation environment on the lunar surface as well as manmade radiation environments from nuclear power supplies (active and spent) and particle accelerator facilities could severely limit the durations and types of manned lunar base operations now currently being proposed. Such natural and artificial radiation environments might also limit the operation and functional capabilities of smart 2nd and 3rd generation lunar robots. For extended lunar base operations, advanced, real-time radiation dosimetry will be required for habitats, workplaces, individual space workers and, quite possibly, radiation sensitive robotic devices.

This paper discusses steps that have now begun to tackle the problem of accurate and reliable real time radiation dosimetry for a variety of lunar base operations. Natural radiation hazards on the lunar surface include solar flares and storms as well as the galactic of cosmic radiation background, with its heavy nuclei or HZE particle content. Artificial or manmade sources in an evolving lunar base/settlement scenario reactors, high energy particle accelerators, and to a lesser extent radioisotope thermoelectric generators (RTGs) that are fueled by the radionuclide, plutonium-238.

In a recent innovative space radiation dosimetry program, hardware that was not initially designed for in-cabin use on the U.S. Space Shuttle, was modified and qualified for man-rated spaceflight and then successfully flown on a number of missions, including STS-6, 8, 11, 41-C, 41-D, 41-G and 51-A. The interesting results obtained from these gamma ray counter and neutron/proton dosimeters are presented in detail. These discussions are complemented by a description of advanced versions of these pioneering dosimetry instruments for future Space Shuttle and Space Station applications. Special emphasis is also given to the need for expanded work in proton and HZE radiology studies, complementary groundbased calibrations, and on-orbit demonstrations of advanced instrumentation prior to the establishment of a lunar base.

A radiation protection strategy for lunar base operations from the initial base to self-sufficient settlement is also presented. Included in this strategy are the use of sophisticated radiation monitoring instruments, a solar flare alerting network, the existence of "radiation storm cellars", and the role of native lunar materials in habitat shielding designs.

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# DRY EXTRACTION OF SILICON AND ALUMINUM FROM LUNAR ORES

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EMEC Consultants suggests to produce silicon, aluminum and oxygen from lunar anorthosite by a dry-extraction process which comprises three major process steps. First, silicon is obtained by reducing the silicon dioxide content of the ore with aluminum metal. The thereby produced aluminum oxide, together with the original content of the ore, is electrolyzed in the second major process step, to yield aluminum and oxygen. In a further step, the calcium component of anorthosite is removed from the system to avoid its accumulation.

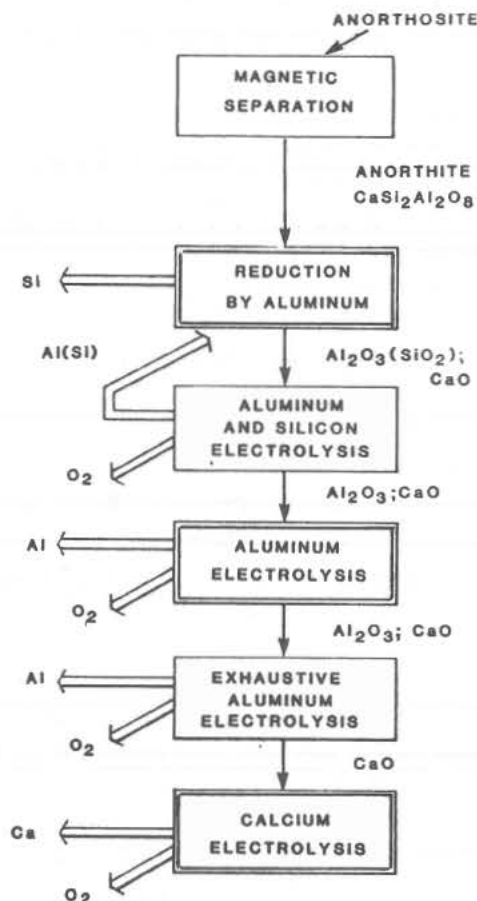
In addition to the three major process steps, a preliminary ore treatment, mainly to remove iron-rich components, may be included. Some additional intermediate process steps may be necessary.

In a NASA SBIR Phase I contract, NAS 9-17575, EMEC Consultants investigated the feasibility of the first major process step, producing silicon metal. Quartz or Wyoming anorthosite were added to cryolitic melt and reduced by metallic aluminum. Recovering the reduced silicon from a resulting hypereutectic Si-Al melt appears most promising.

In the present Phase II, contract NAS 9-17811, work on the first process step continues. Attention, furthermore, is focussed on the calcium removal which appears to be the most difficult process step at this time. In addition to calcium electrolysis, possibilities are investigated to remove the calcium as oxide or as calcium aluminate.

A conceptual effort shall produce a flowsheet of the process and a possible design of a lunar installation to produce 500 t of aluminum, 500 t of silicon and 1000 t of oxygen annually.

The support by the NASA Lyndon B. Johnson Space Center, Houston, Texas, under the Small Business Innovation Research program is gratefully acknowledged. We thank the technical contract manager, Dr. David S. McKay, for his interest and support.



Process Scheme to Extract  
Silicon, Aluminum and Oxygen  
from Lunar Anorthosite

# THE ROLE OF CHEMICAL PROPULSED ROCKETS FOR POINT TO POINT LUNAR SURFACE TRANSPORTATION

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A first lunar outpost at the beginning of the next century will probably initiate a lunar development with a growing number of stations widely spread over the lunar surface. These stations necessarily must be connected with a transportation infrastructure for support by a main base and the rotation of material and personnel between the stations due to their different tasks. Alternative transportation systems, such as electrical driven cars, magnetic levitation railways, mass drivers and rocket vehicles have been identified as possible means of conveyance and compared. A fairly sophisticated model, focused on a comparison of cost-effectiveness has shown that (especially if considering the relative small mass flows during early lunar development) transportation systems with small infrastructure requirements seem to be favorable. In particular, a chemical propelled single-stage rocket, the so-called "Lunar Hopper" emerged as a very attractive vehicle. It's commonality to the lunar ascend/descend stage contributes to this attractiveness. Therefore, this system was analysed in more detail to obtain information about the optimum propellant combination for this purpose. Because liquid oxygen and aluminum can be easily and relatively cheaply produced on lunar surface, but not liquid hydrogen which must be imported at a high price from Earth, the influence of the aluminum content in a LOX/LH<sub>2</sub>/AL tripropellant system on cost-effectiveness was analysed. First results indicate, that the specific transportation costs depend mainly on the vehicle size, transportation volume, mixture ratio and propellant cost. The cost of lunar produced aluminum and that of imported LH<sub>2</sub>, depending on space transportation costs, are the most significant parameters. Thus, the vehicle considered has a maximum payload of about 30 metric tons for the longest distance and a take-off mass in the range of 85 to 215 metric tons. Minimum transportation cost can be achieved for an aluminum content in the fuel between 10 % and 90 % depending on the price of LH<sub>2</sub> and AL on lunar surface.

ADVANCED PROPULSION FOR LEO-MOON TRANSPORT: II. TETHER CONFIGURATIONS IN THE LEO-MOON SYSTEM; James R. Arnold and William B. Thompson; University of California, San Diego, La Jolla, CA 92093.

As members of a group examining advanced propulsion options for the LEO-Moon region, we are reporting on studies of the use of gravity-gradient and spinning tethers. The main virtue of tethers is their ability to function as momentum "banks." They can store and transfer linear and angular momentum, without the use of propellants.

Our study group has examined a number of possible locations and modes of operation of tether systems as part of a two-way transport system between LEO and the lunar surface, the other parts of which are current or projected rocket vehicles (M. Stern, this meeting). Each has specific advantages and deficiencies. We selected three configurations as being worthy of further study. We have compared them with the base case (all rocket) using a number of criteria, of which perhaps most important is the MPR (mass payback ratio). Aerobraking capability is assumed available as required.

One challenging fact was pointed out by our colleague Harris Mayer: the gravitational kinetic energy released when propellant falls from low lunar orbit to LEO is larger than the chemical energy it contains. Can some (or all) this energy be recovered and used?

One of our configurations attempts to do so. It uses a tether platform (TP) in eccentric earth orbit, tangent to that of a LEO platform such as the Space Station. It catches payloads coming down from LLO at a  $\Delta V$  moderated by aerobraking (nominal 1 km/sec), and uses the added payloads upward at comparable velocity. Automated rendezvous and phasing are challenges for this configuration, which has a number of other positive features.

Another configuration is a spinning tether in LEO, which can pick up payloads at suborbital speed ( $\sim 6.5$  km/sec), and later deliver them upward at  $\sim 8.4$  km/sec. Energy makeup is by rocket using lunar oxygen. This too has rendezvous and phasing challenges. It may be a first step in a more elaborate "staircase" system.

Finally we have considered a long hanging tether system in LLO. The tip when pointing down almost grazes the lunar surface, while in the inverted position it moves faster than orbital escape velocity, and can put payloads on track for LEO. This configuration can save much expense fuel transport from LEO. Its challenges include details of the inversion maneuver, tether mass and lifetime.

We are now working with a group of engineers headed by Mike Culp, and including Gus Babb and Mark Sluka, to refine these configurations and identify overlooked problems and opportunities. We are considering also "mixed" configurations, employing more than one advanced propulsion principle.



A NUMERICAL TECHNIQUE FOR OPTIMIZING LOW-THRUST SPACECRAFT TRAJECTORIES IN A THREE-BODY SYSTEM, J.E. Asbell-Clarke (UNM and LANL), M. Houts (MIT and LANL), P.W. Keaton (LANL)

Low-thrust trajectories are a fuel efficient method for moving large masses in a strong gravitational field (e.g. cargo transport from Earth) and also for expedient missions in a weak gravitational field. Optimization of fuel usage has been studied using an analytical two-body approach to the low-thrust trajectory (Keaton, 1986) and numerical codes have confirmed those results. To consider lunar and inter-planetary missions in more detail or to analyze trajectories involving Lagrange points it becomes necessary to incorporate the gravitational effect of at least two masses upon the spacecraft. This is the restricted three-body problem when the mass of the spacecraft is assumed to be negligible with respect to the two large masses.

The three-body code converts the system into a central force problem and the calculations are performed in a rotating reference frame. Maximum fuel efficiency is found using the constraints of the mission specifications such as initial and final values of radial position, angular position, radial velocity, and tangential velocity. The triptime and vehicle specifications are also provided by the user and are used to find the optimum trajectory satisfying those criteria.

It can be shown (Keaton, 1986) that the minimization of the integral:

$$\frac{1}{2} \int_t a^2 dt \quad \text{where } a = \text{instantaneous acceleration}$$

will yield the minimum ratio of propellant mass to initial rocket mass. This code employs the technique of Saltzer and Fetheroff (1961) to minimize this integral by taking the steepest gradient and satisfying both initial and final conditions. These values are specified by the user's mission characteristics.

The user can further minimize fuel consumption by changing the mission specification within allowable guidelines. In general, for a given distance of travel, an increase of the trip duration will decrease the fuel consumption by allowing the spacecraft to spiral out from its origin with a constant acceleration.

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ADVANCED PROPULSION FOR LEO-MOON TRANSPORT: III. MISSION-OPERATIONAL CONSIDERATIONS; Gus R. Babb, Eagle Engineering Inc., 711 Bay Area Boulevard, Webster, TX 77598.

Some of the advanced propulsion configurations being investigated in this study give promise of substantial energy and propellant savings when viewed in two dimensions. Their practical operation in three dimensions, however, may pose serious problems unless significant modifications are made to the original operating concepts. It turns out that while the full theoretical potential of a concept may prove difficult to achieve, carefully devised modifications can often sidestep or eliminate many of the most serious problems while still gaining most of its performance benefits.

The author's task in this study is to identify some of the problems in orbital mechanics and operations presented by the advanced propulsion configurations, and to suggest procedures for their solution or elimination. In this task, the author applies standard mission planning and operations techniques, based on his personal experience, to the conceptual definition of the various advanced transportation configurations. Such techniques include detail weight performance analysis and manifesting through a complete operational cycle. Operations difficult or impossible to achieve given current technology or practice are flagged, and requirements for technology or technique development are estimated.

The elegance of some of the advanced concepts may hide real difficulties when such problems as orbital precessions, launch windows and practical operations are considered. In particular, the configurations involving long hanging or spinning tethers tantalize with the possibility of momentum conservation by "throwing" or releasing outbound vehicles or loads and "catching" inbound ones. They give promise of greatly reducing the  $\Delta V$  required for rocket propulsion, which in turn may result in mass payback ratios considerably greater than unity. At the same time, they pose novel operational difficulties.

To focus on a specific example, as originally envisioned, a conventionally propelled loaded OTV leaves a Space Station in circular LEO to rendez-vous with the tip of a spinning tether attached to a platform in an elliptical orbit, whence it is flung toward the Moon. This poses great difficulties because the circular LEO and the Earth-eccentric elliptical orbit (EEO), both inclined at  $28.5^\circ$ , suffer different orbital regression rates, so their planes rarely coincide.

The relatively simple modification of incorporating a payload dump on the platform in EEO (near the center of mass of the tether-platform system) and having the OTV's operate only between the EEO and the Moon solves this problem. Material from Earth is launched directly to the plane of the EEO rather than to the Space Station. Payload for the Space Station orbit can be "dropped off" by the tether whenever the two orbits precess into the same plane, which occurs approximately every 85 days.

Other examples will be presented.

STUDY OF CHEMICAL COMPOSITION OF ULTRA HIGH ENERGY COSMIC RADIATION  
FROM A LUNAR BASE

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Cosmic ray charged particles of energy above 100 TeV ( $10^{14}$  eV) have a gyro radii in the interstellar magnetic field that is comparable to the size of our galaxy. These particles, therefore, do not suffer much scattering and if these particles are of galactic origin the observations of these particles allows one to view the source. If so, these particles will show an anisotropy in the direction of the source. On the other hand, if these particles are of extragalactic origin then one may not see this anisotropy. Thus a study of the cosmic radiation composition above 100 TeV may reveal the source(s) of this radiation.

The chemical composition and energy of these ultra high energy particles is currently studied by the use of Extensive Air Showers (EAS). As the name implies, these are cascade showers of electrons, muons, and nucleons, produced by the interaction of the primary cosmic particle in the upper layers of the atmosphere. Because of the low density of the atmosphere, the secondary particles are spread out in lateral extent of many kilometers. This makes the detector farms difficult and expensive to run. In addition, only a part of the EAS is sampled by the detectors.

The richness of the EAS in muons is taken as evidence of the presence of heavy nuclei, a totally indirect method. The current meager experimental information, indicates that the relative abundance of heavy nuclei decreases as energy increases and vanishes at energies greater than  $10^{17}$  eV. Much of the evidence at energies greater than  $10^{17}$  eV comes from interpreting multicore EAS as being due to heavy primaries, again a totally indirect method. There is thus a need for a direct charge and energy determination for energies above 100 TeV.

The moon with no atmosphere provides a unique vantage point and offers a chance to study this part of the cosmic radiation that cannot be done effectively from the earth or free flying platforms.

In this paper a method to study the cosmic radiation above about 100 TeV from a lunar base is proposed. This method provides a direct determination of the charge of the primary particle before it interacts with the lunar soil overburden (needed for radiation protection anyway) and produces cascades that are very small in lateral extent (higher density of lunar rock compared to the Earth's atmospheric density) and can be more easily studied. As the flux of these particles is extremely small these detectors systems can be left operating to gather data with minimal attention and thus provide information about the anisotropy. The lunar base thus can be more effectively utilized to provide a basic astrophysics study that cannot be effectively done in any other way.

## GAS JET DIFFUSION FLAMES UNDER REDUCED-G CONDITIONS\*

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The need for an improved understanding of fires is becoming of critical importance with increased space travel and utilization. While the control of fires in space as well as on earth is not understood, it is known that both buoyancy-induced convection and buoyancy-induced turbulence affect ignition, stabilization, propagation, and extinction in low-momentum reactive flows. The objective of this research is to gain a more fundamental understanding of fires, in general and to quantify flame behavior under reduced-gravity levels, in particular. Gas jet diffusion flames are considered in an interactive theoretical and experimental project. Current research on laminar gas jet diffusion flames has shown that under reduced-g levels the flames become larger, globular in shape and more sooty affecting radiation processes and, under some conditions, the flames tend toward extinction [1]. This research involves the study of the combined effects of diffusion, kinetics, radiation and transient phenomena under both normal-g and reduced-g conditions. In the case of turbulent flames, it has been found that both buoyancy-induced convection and buoyancy-induced turbulence affect the flow field structure. Figure 1 shows a comparison between the relative effects of these two buoyancy-related mechanisms (i.e., effects on the mean flow and on the generation of turbulent kinetic energy) in a hot plume under normal-g conditions. The data points correspond to measured temperatures along the axis of the hot plume. Clearly, the prediction gives the best agreement when both mean flow and turbulent interactions are taken into account by the analysis. Theoretical results of this nature have led to the need for data at reduced-g levels, with the requirement for sufficient size and testing time, potentially available in a Lunar-based laboratory.

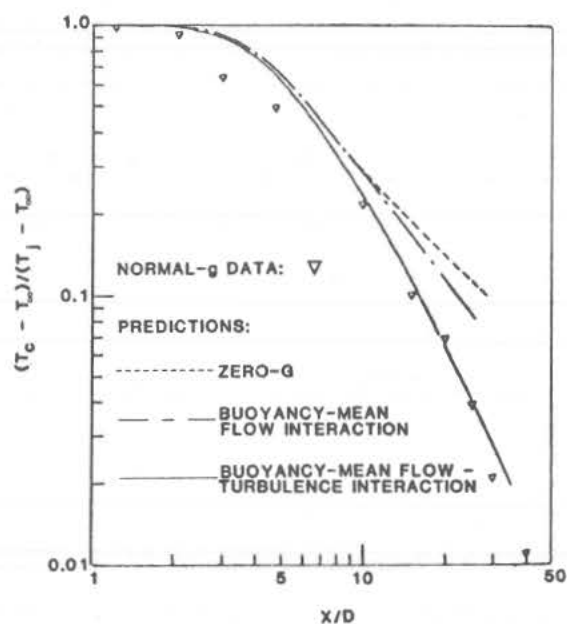


Figure 1: Effect of modeling assumptions on the prediction of centerline temperature for a hot turbulent buoyant jet.

\*This work is supported, in part, by NASA-Lewis Research Center under the PACE (Physics and Chemistry Experiments in Space) program, Contract No. NAS3-22822 with Ms. Sandra L. Olson as the NASA project scientist.

DEVELOPING A SAFE ON-ORBIT CRYOGENIC DEPOT, N. J. Bahr, Webb  
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New U. S. space initiatives will require innovative technology to realize planned programs such as piloted lunar and Mars missions. Key to the optimal execution of such missions are high performance orbit transfer vehicles (OTV's), coupled with large propellant storage facilities. Large amounts of hydrogen and oxygen propellant demand a uniquely designed on-orbit cryogenic propellant depot. Because of the inherent dangers in propellant storage and handling, a comprehensive system safety program must be established. It is shown how the myriad and complex hazards enunciate the need for an integrated safety effort to be applied from program conception through operational use. Even though the cryogenic depot is still in the conceptual stage, many of these hazards have been identified. Some of them are: fatigue due to heavy thermal loading from environmental and operating temperature extremes, micrometeoroid and/or depot ancillary equipment impact (this is an important problem due to the large surface area needed to house the large quantities of propellant), docking and maintenance hazards, and of course the numerous hazards associated with extended extravehicular activity. Various safety analysis techniques are presented for each program phase. Specific system safety implementation steps are also listed. Enhanced risk assessment is demonstrated through the incorporation of these methods.



## AN ASSESSMENT OF LUNAR BASE SURFACE OPERATIONS AND ITS APPLICATION TO COMMUNICATION MODEL DEVELOPMENT

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The characterization of on-site lunar base support operations is a critical step in the design of a communications system. To facilitate the design process, a model is presented which generates a set of communication requirements for a wide range of lunar base scenarios. The key results of each model run are network configuration, system delivery and growth, link budget inventory, and base dependencies (manpower, mobility, and power).

The elements that define the scenarios are divided into four major support categories: science, in situ resource utilization (ISRU), lunar module operations and base infrastructure. The majority of science and ISRU activities are obtained from the NASA maintained Missions and Supporting element Data Base (MSDB). The elements associated with lunar module and infrastructure support are characterized in a lunar base model developed for NASA by the Large Scale Programs Institute (LSPPI). Information such as manpower, data rates, and resupply mass that are available in the MSDB are classified as direct support requirements. Support requirements such as surface transportation, maintenance and servicing, and communication networking are classified as indirect requirements. The indirect requirements are related to operational complexity and are based on current and projected space technologies as applied to a lunar base.

The direct and indirect operational requirements of four lunar base activities, one from each support category, are used to develop operational strategies that can satisfy requirements for the general case. The cases selected for these initial point designs are astronomy, liquid lunar oxygen production, resupply, and command/control. The strategies are then described in terms of basic tasks that can be evaluated as drivers of the base communications requirement. A set of communication system elements are then defined that will be used as building blocks in the communication model. The point designs are also used to establish the parametric relationships linking communication requirements to system deliverables.

The parametric relationships thus established are used to develop a modeling tool that defines a communications system that meets a set of preliminary design requirements. The resulting network configuration reflects various sites in addition to the main base (baselined as near-equatorial). The additional sites were selected to accommodate astronomy facilities on the far side, remote mining operations for ISRU, and selenology experiments. Crew operations proved to be a high-impact factor in defining the communications system. Therefore, considerable attention is placed on manpower management during the discussion of operational strategies. As a final step in the modeling process, the base dependencies are fed through the comprehensive lunar base model to account for any manpower, transportation, or power needed to operate the communications system itself.

## **CONSTANT TEMPERATURE VESSELS FOR LUNAR BASE APPLICATIONS**

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AS LUNAR BASES ARE DEVELOPED, THERE WILL BE A MYRIAD OF EQUIPMENT ITEMS WHICH WILL HAVE TO BE HEATED DURING THE LONG LUNAR NIGHT AND COOLED DURING THE LONG LUNAR DAY. CONSTANT TEMPERATURE VESSELS WILL PROVIDE NECESSARY HEATING AND COOLING.

THE MOST SIGNIFICANT FEATURES OF THE VESSELS IS AS FOLLOWS:

THE VESSELS WILL BE ABLE TO BE OPENED OR CLOSED EASILY.

THEY WILL CONTAIN LUNAR MATERIAL.

A VESSEL WILL BE CAPABLE OF BEING COLD SOAKED DURING THE LUNAR NIGHT OR HEAT SOAKED DURING THE LUNAR DAY.

A COLD SOAKED VESSEL WILL BE CLOSED AND ITS CONTENTS USED FOR COOLING DURING THE LUNAR DAY. HEAT TRANSFER CAN BE ACCOMPLISHED VIA A GAS MEDIUM SUCH AS NITROGEN.

SIMILARLY, A HEAT SOAKED VESSEL WILL BE CLOSED AND ITS CONTENTS USED FOR HEATING DURING THE LUNAR NIGHT.

SIZES OF CONTAINERS CAN BE VARIED FOR THE VARIOUS USAGES. THERE NEEDS TO BE SUFFICIENT LUNAR MATERIAL TO PROVIDE THE HEATING OR COOLING REQUIRED. SIZING CALCULATIONS WILL INCLUDE BTU DATA FOR SOAKED MATERIAL, HEAT TRANSFER EFFICIENCY, LUNAR SURFACE TEMPERATURES, AND LENGTH OF USAGES OF THE VESSELS FOR EACH CYCLE.

THE AUTHOR HAS A PATENT DOCKET FOR THIS SCHEME.

Experimentation and System Modeling Efforts in Support of Space Power Systems  
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The successful exploration and colonization of space depends on the availability of a reliable space power system. Because of the stringent requirements the space environment places on such systems, they will have to be more reliable and much better understood than their terrestrial counterparts. Understanding the performance of space power system advanced heat transfer devices and mechanisms under a variety of conditions is a prerequisite for their design and operation.

Coordinated efforts involving system modeling and experimental investigations of heat transfer mechanisms and components are being conducted at Texas A&M University. In conjunction with NASA JSC, a series of microgravity experiments are in progress. The test package consists of a two phase flow boiling and condensing loop with temperature, pressure, power and flow measurements at various points along the loop. The boiler consists of a nichrome wire wrapped clear quartz tube in which boiling of the water working fluid is observed. A three piece clear glass condensing section allows direct observation and temperature and pressure measurements of the two phase condensing flow. A high speed camera is used to record flow regime data and a PC-XT using a data acquisition package collects the measurements to be stored for later analysis. Over one hundred zero-g parabolas on a KC-135 have enabled a condensing two phase flow heat transfer coefficient determination to be made and a microgravity two phase flow regime map constructed.

A rapid transient heat pipe test facility is operating under Air Force funding. An insulated rectangular aluminum heat pipe is used to obtain pressure, vapor, liquid and wall temperature measurements during startup and power transients. The heat pipe is equipped with a clear glass cover that allows direct observations of phenomena that occur within the pipe during a variety of transients including frozen start-up and step changes in power input and output. Supporting this experimental effort is a heat pipe transient modeling computer code development task. The completion of this code will allow direct comparisons of modeling assumptions and experimental measurements.

Two projects involving space power system modeling include a comparison of nuclear and solar options for a follow-on space station and a detailed system simulation of an SP-100 type space nuclear power plant. In conjunction with NASA-JSC, a solar dynamic power system is being modelled to explore design alternatives including a comparison of the solar dynamic system with a nuclear system on the basis of overall efficiency and system mass. Funded by the General Electric Corporation, the nuclear power system simulation is an end-to-end model that includes a study of the simultaneous transient behavior of the nuclear reactor heat source, the mass flow rate of the liquid lithium used to transport energy through the system, the self-induced thermoelectric-electromagnetic pump, the thermoelectric energy converters, the heat pipe radiators, and the power conditioning system. This generic computer model will be used to test the impact of design changes on system performance.

These projects allow an approach to the study of space power system components and processes that range from basic research to full power system simulations and provide essential information for the exploration and colonization of space.



## MODELING A LUNAR BASE PROGRAM

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This paper addresses the development and application of the methodology used by the Large Scale Programs Institute and NASA Johnson Space Center to construct a strategic planning tool for advanced space missions. Specifically, a personal computer-based model of a lunar base program is discussed. The top-level development of the model on Lotus Symphony Version 1.1 is described with flow diagrams and inter-relationships between the various technical disciplines defined. In addition, application of this modeling methodology to a Mars exploration program is identified.

The input/output interface of the model is the Civil Needs Data Base which is maintained at NASA Headquarters. The model user is asked to select various science and in situ resource utilization elements from the data base and the year he wishes them operative on the lunar surface. The model uses this information to define precursor, construction, support, and resupply requirements for each selected element collectively per year. The model user then selects a transportation fleet which the model uses to construct a flight schedule to complete the desired scenario. Top-level details of the resulting scenario are the outputs of the model; however, access is provided to the details of the modeling of each technical discipline.

The lunar base model is segmented into modules dedicated to dedicated to specific technical areas such as surface habitation, thermal control, and space transportation. This method allows for efficient model development and easy modification to individual modules. Each of the modules is defined and its top-level logic and data sources identified. The flow of data between the various modules forms the structure of the lunar base model, which will be traced to show the model's usefulness as a strategic planning tool.

Finally, results of various impact and sensitivity analyses using the current version of the model are given for the reader to fully appreciate the model's capabilities. Scenarios used for these analyses were generated within the NASA advanced space planning community.

## **LUNAR BASE PROGRAM IMPACTS ON THE PROPOSED LOW-EARTH ORBIT SPACE STATION**

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This paper characterizes the requirements a lunar surface base program places on the NASA Space Station in low-Earth orbit (LEO). Two characterizations of the requirements in LEO are detailed, one compiled from the capabilities of the proposed NASA Space Station, and the other derived from the needs of a permanently manned lunar base. The results of the characterizations are compared and contrasted in several specific areas, including: space transportation system operations and support, launch vehicle and orbital transfer vehicle berthing facilities, extravehicular activity capabilities, Space Station power requirements, communications and tracking for guidance and navigation, manpower requirements, and payload interfaces for reconfiguration and flight manifesting.

Space Station capabilities are evaluated from current NASA baseline requirements determined by the NASA/Johnson Space Center Space Station Programs Office, and are projected based on expected growth. Particular attention is devoted to Space Station functions, architecture, systems, and sub-systems that are highly impacted by a developing lunar base.

Lunar base requirements are assessed using the Lunar Base Model developed at the Large Scale Programs Institute in conjunction with the NASA/Johnson Space Center Advanced Programs Office. The simulation technique and methodology employed by the model are explained, with emphasis on the transportation and infrastructure requirements in LEO. Three development scenarios are detailed for early, mid-term, and late configurations of the lunar surface base, as prescribed by the NASA advanced programs community, including the National Commission on Space and the Ride Report to the NASA Administrator. The results of the simulations define the capabilities that must be present at the Space Station in support of each scenario.

The results of the comparisons show the restrictions that the present Space Station configuration will place on lunar base support, or the need for more robust facilities in LEO to adequately pursue the development of a lunar base. The possible construction of a transportation node in LEO dedicated to support of the lunar base program is addressed according to needs of the various scenarios.

## A LUNAR ELECTROMAGNETIC LAUNCHER

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and  
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This paper discusses a lunar surface electromagnetic launcher concept and supporting systems characterized by the Center for Space Research and Center for Electromechanics at The University of Texas at Austin. The emplacement and operation of the launcher system, which delivers one metric ton of liquid oxygen to the low lunar orbit per payload launch, is addressed. The comparatively larger payload capacity of the projectile designed in this study reduces the number of launches cited by previous designs. The addition of an apolune kick motor to the payload module eliminates the need for an on-orbit payload "catcher" utilized by most other concepts.

A passive coaxial accelerator is used to propel the 1240 kilogram (wet) payload module and 2000 kilogram thermal protection carriage the length of the gun at 3000 times that of Earth's gravity. The 68-meter gun consists of nineteen sections, two of which are used to decelerate the carriage as it remains on the surface for reuse. The first three sections of the accelerator are used for cooling the carriage, loading the payload module, and rotating the projectile assembly for ballistic flight stability, respectively. The remaining sections of the launcher accelerate the payload module to 1687 meters per second in order for it to obtain an apolune altitude of 100 kilometers.

To assess the impacts of the proposed lunar launcher, a fleet of space transportation vehicles were assumed in place and operational to provide delivery and support functions. Time to "break even" is selected as the economic value model in this study while the liquid oxygen market in low Earth orbit is used as the system driver. The "break even" point is calculated in terms of accumulated Earth-launched mass with the investment mass of the launcher taken into account. Given a total system mass of 2390 metric tons and a net liquid oxygen requirement in low Earth orbit of 1000 metric tons per year, the time to "break even" for the launcher system (in lieu of lunar modules using conventional hydrogen/oxygen propulsion) is approximately 11.5 years. As a conservative measure, no lunar-derived materials other than liquid oxygen are used to aid in the delivery, construction, or operation of the launcher system; however, in situ materials that could reduce the time to "break even" are identified qualitatively. The economic assessment of this launcher concept does not address the time value of liquid oxygen in low Earth orbit.

## DELIVERING LIQUID OXYGEN TO LOW EARTH ORBIT

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This paper addresses the question of delivering the low Earth orbit liquid oxygen requirements from either the lunar surface or the Earth. Decision theory is used as the analysis method to determine the most economical delivery scenario given the investment cost of producing liquid oxygen on the Moon. The economic model used to compare the two alternatives is the time to "break even" (if one occurs) for the lunar delivery scenario, as compared to Earth delivery, in terms of accumulated Earth launched mass.

Decision theory consists of three distinct phases. The first is the deterministic phase in which engineering evaluation and modeling is conducted in order to perform sensitivity analyses on key technological systems. The second, or probabilistic, phase is used to encode probabilities to the range of values for preselected, high-impact variables in the deterministic model. The last phase, which is called the informational phase, determines the value of obtaining further information on some of the variables identified in the probabilistic phase. The three phases are detailed for liquid oxygen transport to low Earth orbit, and the two delivery options are compared.

The results of the study, given no perfect information on pre-selected state variables, show that oxygen should be supplied from the Earth as the time to "break even" for the lunar supplied scenario approaches approximately 22 years. Information leading to a more accurate assessment of the oxygen content of the lunar regolith is shown to be worth 2.2 years of the cost of the Earth-supplied program. Acquisition of the actual content of the lunar regolith is discussed as it applies to the decision to supply the low Earth liquid oxygen requirements from Earth or the Moon.

## EVOLVING LAVA TUBE LUNAR BASE SIMULATIONS WITH INTEGRAL INSTRUCTIONAL CAPABILITIES

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We propose to create one or more facilities in central Oregon for the simulation of lunar base facilities in a lava tube environment. Hörz (1984) details the economic and operational advantages of lunar lava tubes. Our program uses terrestrial lava tubes to build stepwise into a realistic simulation of a lunar base and support system. Several areas of technology can be investigated, including structures, recycling, and energy systems. A parallel instructional capability allows demonstration exercises earlier in the project. The full simulation of structures and organization for a lunar base in a lava tube will be phased in as the instructional facilities grow in sophistication and scale. In the summer of 1987 we conducted site and feasibility studies and obtained USFS permission to use one lava tube in further exercises. In order to apply actual field data to the design process, Young Astronauts and SEDS workers set up modular workstations and performed predefined tasks in and around the lava tube base. The results of our simple simulations suggest that the advantages of a lava tube base outweigh the problems. We feel an ongoing lunar base simulation in a terrestrial lava tube offers many opportunities for design, operational simulation, and education. We seek sponsors and funding for further development and exercises.

Hörz, Friedrich, "Lava Tubes: Potential Shelters for Habitats", in Mendell (ed.), Lunar Bases and Space Activities of the 21st Century, Lunar and Planetary Institute, Houston, 1984

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LUNAR BASE ORBITAL SCIENCE: LUNAR MAPPING-, MONITORING-, AND SHORT-LIVED PHENOMENA- ORBITERS; Alan B. Binder, Lockheed EMSCO, 2400 NASA Rd. 1, Houston, TX 77058

There is agreement that a Lunar Polar Orbiter Mapper must fly to provide global data on the Moon's surface composition, gravity and magnetic fields, topography, etc. prior to establishing a Lunar Base. Given that ~20 orbital experiments can provide information about the Moon and the need for high resolution (1 m), global photography, more than one such mission should be flown.

Beyond these mappers, two additional types of orbiters are needed - Lunar Monitoring Orbiters and Short-Lived Phenomena Orbiters. As was confirmed by Apollo, things do happen on the Moon.  $^{40}\text{Ar}$  is released from the Moon (1), perhaps by shallow moonquakes (1,2). Radon is released from such craters as Aristarchus and Grimaldi and, as delineated by deposits of radon's decay product polonium, along the fractures at the edges of the maria (3). 10 km scale thrust fault scarps are developing as a result of shallow moonquakes (4). The natural lunar atmosphere is in a constant state of change as it is lost by UV ionization/solar magnetic field sweeping and replenished by solar wind H and He and the release of lunar  $^{40}\text{Ar}$  and other gasses (5). As manned activities increase, rocket exhaust products and life support leakage will build up an atmosphere many times more massive than the natural one (6) and may lead to the formation of an ionopause and bow shock. Impacts release volatiles and form 100 m scale craters every 10 years (7). These impacts may change or generate new local magnetic fields (8). Understanding these phenomena is an important part of lunar science.

Some of this activity can be monitored by a moon-wide network of seismometers, mass spectrometers, UV spectrometers, etc. However, adequate monitoring of the atmosphere, the release of radon and the deposition of polonium, and the lunar-solar wind interactions can only be accomplished by 2 or 3, long duration, spin stabilized Lunar Monitoring Satellites in 100 km polar orbits.

These monitoring satellites and the seismic network will also alert scientists at the base when- and locate where- a gas release event, shallow moonquake, or >100 m crater forming impact occurs. Within 10 - 30 minutes of the detection of an event, a Short-Lived Phenomena Orbiter would be launched into a 50 km orbit. The inclination of orbit would be chosen to allow several close passes over the site, during which large amounts of data would be collected on the release of gas, changes in the magnetic field and surface morphology, etc., in order to document the event.

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LUNAR BASE SITE SELECTION: LUNAR RESOURCE CRITERIA;  
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The selection of the Lunar Base site will depend on a number of criteria, such as the availability of ice near the poles (1) and the major objectives of the base, e.g., lunar science, lunar resource utilization, etc. I assume for the following that ice does not exist near the poles and that lunar resource utilization is a major factor in determining the Lunar Base site.

Haskin (2) argues that resource processing techniques should be simple and inexpensive, even if they yield limited products. An example is the  $H_2$  reduction of ilmenite ( $Ilm$ ,  $FeTiO_3$ ) to produce  $O_2$  and  $Fe$  (3). This philosophy is questionable. It is often the case that a higher initial investment brings a quicker and more substantial payback. Consider the  $Ilm$  process: the highest  $Ilm$  content of soil is 12% (Apollo 17 soil), so  $Ilm$  reduction would yield only 1%  $O_2$  and 4%  $Fe$ , whereas such soils contain 42%  $O_2$  and 14%  $Fe$ . Considering the work needed to move and process the raw soil, it may be more economical to start with a more complex process (e.g.,  $NaOH$  electrolysis or fluorine reduction (4)) which yields all the  $O_2$  and all the other soil constituents.

Assuming that the latter approach is adopted, then Lunar Base site selection depends mainly on finding the optimum resource location. Though  $O_2$  may be the most important product, the  $O_2$  content of lunar soils is quite uniform at 42-45%. So  $O_2$  is not a determining factor. This is also the case for  $Si$  which varies only from 19-23%. The remaining major components vary significantly between the end-member soils of the  $Ti$ -rich maria and the anorthositic highlands ( $Ca$  7-11%,  $Al$  5-15%,  $Mg$  3-8%,  $Fe$  3-15%, and  $Ti$  <1-6%). These variations are not so great (except perhaps for  $Ti$ ) that they will influence site selection.  $Ca$ ,  $Al$ ,  $Mg$ , and  $Fe$  are available at 6-10% (within a factor of 2 of their maximum levels) and  $Ti$  is at 1-2% at sites of intermediate composition (highland gabbro and norite soils). Thus the major resource elements can be obtained at significant levels at numerous locations with intermediate soil compositions. Therefore, site location does not depend critically on the availability of the major elements.

In contrast, the concentrations of minor and trace elements, especially those associated with KREEP, vary widely in lunar soils and might be found in very high concentrations in KREEP-rich regions. Many of these elements are very important for the development of lunar industry, agriculture, etc. Thus the critical criterion for choosing the base site may be that it has economic levels of trace elements. Since KREEP is genetically associated with some gabbroic and noritic materials, such soils offer both economic levels of the major elements and the potential of significant trace element deposits. The Fra Mauro Formation, the Apennine Bench, and the Aristarchus Plateau are candidates for such sites.

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LUNAR LANDING VIA A LINEAR ACCELERATOR; Alan B. Binder,  
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Using mass drivers or linear accelerators has long been considered a way of launching payloads into lunar orbit from the airless moon (1,2). The major advantage of this technique is that it uses electrical energy rather than chemical propellant to achieve the required 1.7 km/s orbital velocity. As is well known, chemical propellants are expensive (even if lunar  $O_2$  is used), whereas solar energy can be obtained very cheaply on the moon. There is however a second consideration: The build up of a man-made lunar atmosphere via rocket exhaust products and life support system leakage once manned lunar activities have reached a certain level (3).

The natural lunar atmosphere has a total mass of about 10 tons (3). Note that a single Apollo landing brought to the Moon an equivalent amount of exhaust gasses, which took a few months to be removed from the lunar environment by UV ionization/solar magnetic field sweeping. As discussed by Vondrak (3), manned activities can quickly lead to the build up of a more massive lunar atmosphere, which will be stable for very long periods of time (>100's to 1000's of years). Such an atmosphere will interfere with certain types of astronomical observations and with linear accelerator launching. Thus, any means which can be employed to reduce the amounts of exhaust gasses introduced into the lunar environment should be seriously considered. Clearly the launching of payloads by linear accelerators offers this advantage.

Currently linear accelerator systems are being developed to launch small payloads, mainly lunar soil and lunar  $O_2$  containers. Larger systems (to be sure - low acceleration systems) can be used to launch large carriers of cargo and people. However, to my knowledge, no one has considered the obvious possibility of using linear accelerators to land deorbiting vehicles - manned or unmanned. The use of such a launch/landing system would not only improve the economics of lunar transportation, but would totally remove a major source of the man-made atmosphere.

Simple orbital calculations show that a vehicle in a landing, elliptical orbit with an apoapsis 100 to 300 km above the surface and a periapsis a few meters above the surface spends 20-30 sec. within 5 meters of the periapsis altitude. Given an approach, laser tracking system spread out several 100 km along the approach path and high speed computers, it would not be difficult to 1) accelerate the linear accelerator's launch/landing sled to 1.7 km/s a few km up range of the periapsis point at the appropriate time, 2) maneuver the landing vehicle so that it is exactly over the sled as it approached periapsis, 3) cause a mechanical capture of the vehicle by the sled within the 20-30 sec. capture period, and 4) cause the vehicle and sled to decelerate, thereby finishing the landing sequence.

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## NUCLEAR REACTOR POWER SYSTEMS FOR LUNAR AND PLANETARY BASES

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A preliminary feasibility study of the issues associated with the application of nuclear reactor power systems to manned planetary surface base missions has been conducted. The purpose of the study was to identify and assess the performance, safety and shielding technology options for reactor power systems integration with an evolutionary manned surface base scenario. The requirements and characteristics of a variety of human-rated modular reactor power system configurations selected for a range of power levels from about 10 kWe to hundreds of kilowatts are described. Trade-off analyses for reactor power systems using both earth-made and indigenous surface shielding materials are provided to examine performance, installation and operational safety feasibility issues. The capability for power level growth with increasing manned presence, while maintaining safe radiation levels and maximizing surface activity utilization was investigated. An unshielded surface base modular growth power plant layout was developed to provide a low mass, low cost, minimal installation activity concept.

Preliminary study results have not identified any feasibility limitations or barriers that would impede further studies of the nuclear reactor option for manned planetary surface base power.

**MODELING CONSTRUCTION REQUIREMENTS  
FOR A MANNED LUNAR BASE**

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Before accurate modeling and planning of a manned, lunar base can be accomplished, a methodology representing the construction-and-assembly process of lunar surface facilities must be developed. This paper presents the status of the authors' efforts in the development of a lunar construction-and-assembly methodology which will be used in the modeling and planning of a manned, lunar base.

Various construction-and-assembly tasks and items which influence the duration, manpower requirements, and equipment requirements of the tasks are identified. Decision analysis techniques are used to determine the most desirable values for decision variables, such as task integration procedures, and to identify critical state variables which will require further investigation and refinement.

The methodology for parametrically representing the construction-and-assembly process for various lunar surface facilities will be incorporated into a comprehensive "Lunar Base Model" being developed by the Large Scale Programs Institute, Austin, Texas. The construction-and-assembly portion of the model will produce facility and equipment delivery schedules, manpower loading schedules, and equipment mass estimates which will affect the overall launch schedule and launch mass estimates of the lunar-base program.

The design data are being developed by NASA, in the form of a mission data base in which approximately 40 different missions and facilities will be defined. Construction techniques and data will initially be adapted to the lunar environment from terrestrial methods.

## COMPUTATION OF SELENOCENTRIC ORBITS USING TOTAL ENERGY:

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The precise computation of selenocentric orbits for long time intervals is difficult because of the unusual shape and density distribution of the Moon and because of the large perturbing influence of the Earth on selenocentric orbits. This task can be made considerably easier by the use of any of several new formulations (Reference (1), (2), (3)) of the perturbed two body problem which consider the total energy of the orbital system as one of the dependent variables. The total energy is the osculating two body energy plus the potential energy due to perturbing masses. The use of the total energy as the dependent variable instead of the two body energy is a relatively new idea (Reference (1)). The advantage of using total energy arises from the fact that the more perturbing potential energy that is accounted for in the total energy variable, the more nearly constant is the total energy. In fact, except for dissipative forces such as drag, the only reason for the total energy not being constant is the rotation or revolution of the perturbing mass. This near constancy of the total energy has the effect of inhibiting error growth during numerical solution (Reference (1)).

One of these total energy formulations (Reference (2)) was used recently in the refinement of the computation of geocentric satellite orbit perturbed by a geopotential of 30th order and degree. This application showed a remarkable increase in precision and a decrease in computer effort of 25 percent over a similar computational method which did not use the total energy as dependent variable.

This paper will present the results of an application of total energy formulation (Reference (2)) to the problem of the precise computation of selenocentric orbits.

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THE BENEFITS OF DIRECT NUCLEAR PROPULSION FOR CISELUNAR SPACE TRANSPORTATION AND LUNAR BASE DEVELOPMENT, S. K. Borowski, Sverdrup Technology, Inc., Lewis Research Center, Cleveland, Ohio 44135.

The recently completed Ride report [1] has recommended a manned lunar base as NASA's next major space initiative. A return to the moon is an attractive option for the U.S. space program because it is a logical follow-on to Space Station and can serve as a catalyst for developing the advanced technologies and life sciences information needed for future manned planetary missions. The cargo requirements for establishing and maintaining a permanent scientific base are significant. Babb [2] has estimated that ~5600 metric tons must be launched to the Space Station over a ten year period to support lunar base construction. Approximately 70% of the total cargo would be LOX/LH<sub>2</sub> propellant used by two chemical OTVs which comprise Babb's cislunar transportation system. The launch cost for this much propellant using the space shuttle (at \$5000/kg) or a heavy lift launch vehicle (at \$1000/kg) is estimated at ~\$20B and \$5B, respectively.

Fuel efficient direct thrust nuclear thermal rockets (NTR's), with their higher specific impulse (~850s - 1000s for current NERVA and particle bed reactor (PBR) technology and ~5000s for advanced gas core reactor (GCR) concepts), can greatly increase the effective payload transported to a lunar base compared to chemical systems. Mission duration is also short (~72 hours for 1 way transit) compared to electric propulsion systems [3]. Direct nuclear propulsion was originally considered by NASA for use in the Apollo program. Budgetary reductions and slippage of the Rover program schedule, however, prevented its implementation. An advanced Saturn V with a NERVA-powered S-IVB stage ( $F = 330\text{kN}$  and  $I_{sp} = 850\text{s}$ ) could have propelled nearly 90 metric tons of payload to lunar transfer velocity thereby providing the Apollo program with a direct lunar landing capability. Studies [4] also showed that the nuclear Saturn system could transport sufficient cargo to establish a 20 man lunar base in approximately a year's time.

In this paper the payload carrying capacity for an advanced cislunar transportation system based on NERVA, PBR and GCR technology is examined. Because less than 0.1% of the U-235 fuel inventory is consumed during a typical 20 minute NERVA translunar insertion burn, reusable, as well as expendable NTR's will be investigated. The Flight Engine Program (FEP), developed by Aerojet during the NERVA program, is used to compute nuclear rocket performance for various cislunar mission scenarios involving engine shutdown, coast, and restart cycles. The FEP program also determines cooling requirements for control of reactor afterheat and has been used previously for ground test and flight engine studies [5]. Engine concepts will be compared in terms of IMEO (an indicator of mission cost), payload and propellant mass fraction and triptime. Issues such as refueling, maintenance and repair of radioactive nuclear engines will also be addressed.

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## Lunar Base Construction Equipment

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Described is a system of equipment intended for site preparation and construction of Lunar Base. The proximate era of Lunar exploration and the initial phase of outpost habitation are addressed. Drilling, mining, and beneficiation of Lunar soil preparatory to pilot-plant oxygen extraction and other processing are also within the scope of the system's capabilities.

The centerpiece is a mobile work platform described in more detail by the authors in a paper entitled "A Three-Legged Walker". Modular in nature, the system includes a series of interchangeable implements whose individual use tends to be seasonal or intermittent. Somewhat analogous to the farmer's tractor and implement set, the proposed system is mechanically simple and weight-efficient.

Conceptually somewhat different from their earthbound counterparts, the implements are designed to take advantage of the Lunar environment and to operate within the constraints it imposes.

The walker's implement interfaces can also be used for transporting containerized cargo on the Lunar surface. A proposed Lunar orbit to Lunar surface landing pod might also be used to deliver the walker and crane boom combination in a ready-to-work configuration.

### A Three-Legged Walker

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The three-legged walker is proposed as a mobile work platform for numerous tasks associated with Lunar Base site preparation and construction. It is seen as one of several forms of surface transportation, each of which will be best suited for its respective tasks.

Utilizing the principle of dynamic stability and taking advantage of the Moon's gravity, it appears to be capable of walking in any radial direction and rotating about a point. Typical curved path walking could involve some combination of the radial and rotational movements.

Comprised mainly of a body, six actuators, and six moving parts, it is mechanically quite simple. Each leg connects to the body at a hip joint and has a femur, a knee joint, and a tibia that terminates as a foot.

Also capable of enabling or enhancing the dexterity of a series of implements, the walker concept provides a mechanically simple and weight-efficient means of drilling, digging, mining, and transporting Lunar soil, hoisting equipment, transporting containerized cargo, and performing other like tasks.

A proof-of-principle machine has demonstrated the feasibility of the walking concept.



"MULTIPLE VEHICLE, LOW ORBIT BASES"

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In proposing a permanent lunar base, we are concerned that a permanent base within itself, would be less productive than having an on going exploration of the lunar surface by mobile vehicles.

To be more specific, our group feels a multiple force of low orbit vehicles designed to house 10-15 persons each, and equipped to mine through spectral/chemical analysis, as well as perform many other scientific endeavors in various locations, would be much more equitable. This system of mining would be more lucrative due to the larger yields of base elements that a mobile group of vehicles can deliver, as opposed to that of a stationary base. This gives the capability of researching large quantities of lunar surface using spectral analysis to locate elements most useful for production of required end products, while offering various country's governments and private venture funders the best value for their dollar.

By using three or more ships, each isolated from the other, they become independent life support systems housing specialists from many disciplines. This concept insures a higher probability of survival for all involved, as opposed to having a specific base which would house all individuals.

A few concepts for surface operations in the use of these mining ships would be to have a complete production facility on each ship, which would mine, analyze, and separate elements into separate, inflatable storage tanks; or, have the three ships as "gatherers" with one central base for processing. As the gatherers reach out to locations further from the central base, other new bases could be added. Separate "transport carriers" would meet the gatherers at distant locations and exchange their empties for the gatherers' full load, then transport them back to a central base for processing.

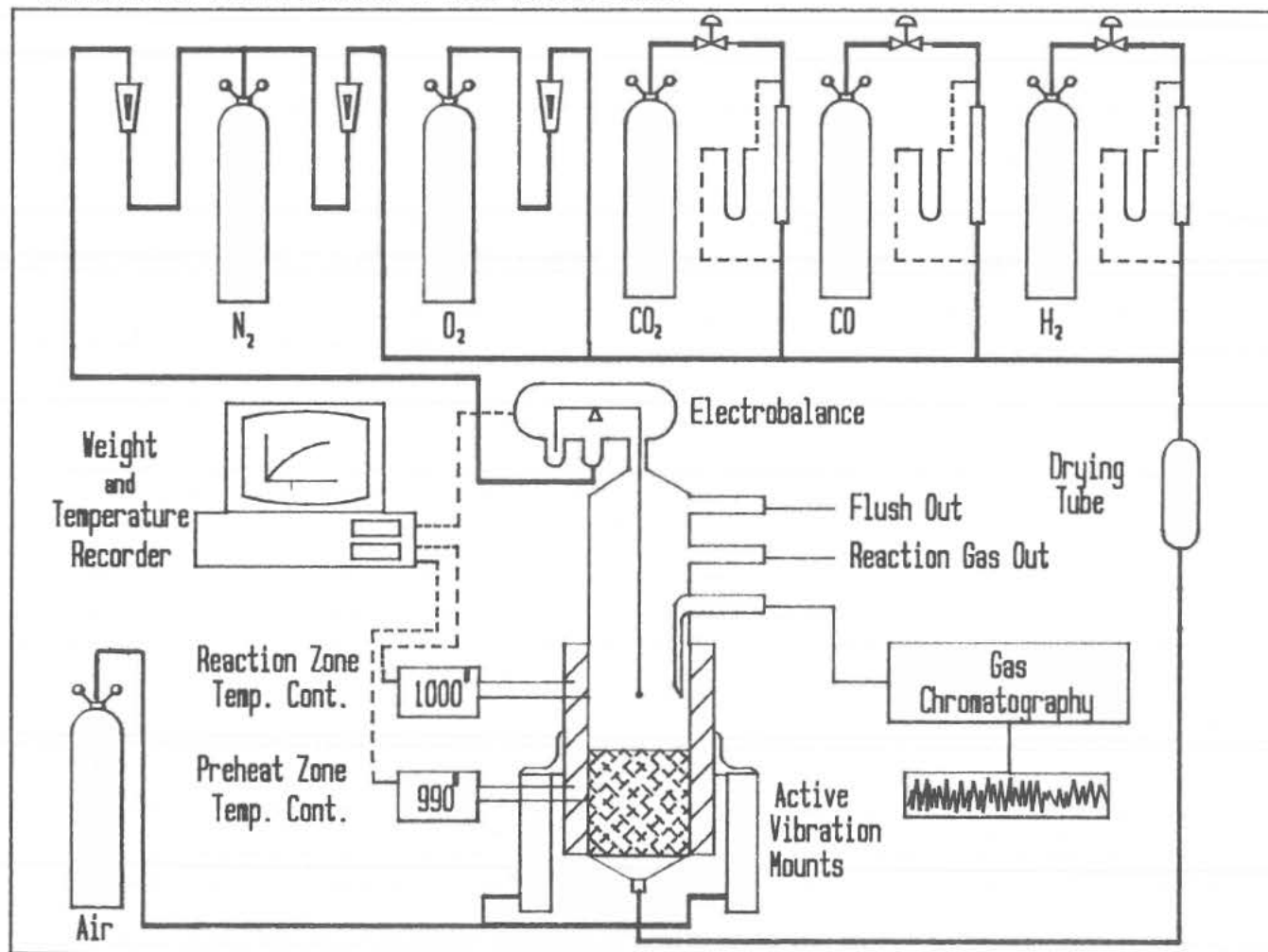
In our contention that multi vehicle low orbit bases should be the design for future lunar inhabitants, we also realize that the initial configurations for the implementation is critical in its operation and expense. But we also feel the long term benefit will, in information gained, and profits earned, far outweigh the plans and time invested today.

OXIDATION AND REDUCTION OF ILMENITE; APPLICATION TO OXYGEN PRODUCTION ON THE LUNAR SURFACE. R.A. Briggs and A. Sacco, Jr., Department of Chemical Engineering, Worcester Polytechnic Institute, Worcester MA 01609.

Ilmenite ( $\text{FeTiO}_3$ ) is a potential source of oxygen in the lunar soil. One method to obtain this oxygen is to reduce the ilmenite in the solid state with hydrogen. A major problem confronting the reduction process is the low conversions of hydrogen to water, less than 5% per pass conversion at temperatures under 1000K. As past studies from this laboratory have indicated however, preoxidation with oxygen, carbon dioxide and water can all be used to increase the rate of ilmenite reduction. It was concluded that the enhanced reduction was due not only to the precipitation of a separate iron oxide phase, but also to alteration of the solid morphology. To quantify the effects of preoxidation of these gases on the rate of ilmenite reduction this study has developed the system diagrammed in the figure below.

The thermogravimetric reactor system for this study consists of three subsections, a gas delivery system, the vibration isolated reactor assembly housing, and a data acquisition system. The gas delivery system was designed to provide precise quantities of  $\text{CO}_2$ , , and  $\text{H}_2$  by measuring the pressure drop over meter long precision bored capillary tubes. The reactor subsection consists of a two-zoned furnace mounted on an adjustable table beneath a CAHN 2000 electrobalance. The assembly is isolated from vibrations by three active vibration mounts eliminating background noise to the electrobalance. The data acquisition subsection logs the temperature of the two zones of the furnace and the weight of the sample through a 12-bit analog to digital converter. Software developed during the study allows for data manipulation and graphing.

With testing of the system now complete, the study is directed along two initial directions. Precise delivery of  $\text{CO}$  and  $\text{CO}_2$  will allow for the synthesis of a close lunar analog ilmenite sample by controlling the oxygen fugacity in the furnace. Once synthetic ilmenite is formed oxidation and reduction studies will begin. Results will be presented on these initial studies.





ADVANCED PHOTOVOLTAIC POWER SYSTEM TECHNOLOGY  
FOR LUNAR BASE APPLICATIONS

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Establishment of a permanent manned presence on the moon will be a severe challenge, not the least part of which will be to provide a source of power. Since a lunar base may well experience evolutionary development in size, capability and complexity, power requirements will also exhibit an evolutionary growth from an initial tens of kilowatts level to an ultimate level in the megawatt range. It is commonly held that the latter will require a nuclear reactor power source to minimize the weight that must be launched to the lunar surface. It is quite likely, however, that the initial base will require an easily deployed system for start-up and early operations. It is also reasonable to assume that the first phases of growth will depend on modular expansion of the initial power system until the SP-100 nuclear system can be incorporated into the base. Since the SP-100 is designed to supply 100KW<sub>e</sub>, system changeover would not be expected to occur until that level of power becomes a modular unit. This paper will discuss and compare advanced photovoltaic/electrochemical (batteries or regenerative fuel cells for storage) power system options for a lunar base, and will compare estimated system masses with those projected for the SP-100 nuclear system. The results of the comparison will be quantified in terms of the mass saved in a scenario which assembles the initial base elements in LEO and launches from there to the lunar surface. A brief summary will be given of advances in photovoltaic/electrochemical power system technologies currently under development in the NASA/OAST program. A description of the planned focussed technology program for surface power in the new Pathfinder initiative will also be provided.

## AN ALL ELECTRONIC TRANSPORTATION SYSTEM FROM LEO TO GEO AND BEYOND

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**System description and moon mission interface.** The all electronic LEO to GEO transportation system (1) now being studied by NASA as part of the space transportation infrastructure and that combines the high specific impulse of the ion thruster with beamed microwave power may have application to a moon or Mars mission. The range of the system can probably be extended to twice GEO distance where 80% of the delta V required for the moon mission will have occurred. In principle the electronic OTV (orbital transfer vehicle) transports the moon mission to twice GEO, comes back to perform its routine LEO to GEO function, and then later retrieves the mission when it returns from the moon. The system schematic and a diagram of the complete, four beam system are shown in Figure 1. All elements of the system must be located in the equatorial plane to allow beam contact with the OTV each time it orbits the earth. This location is consistent with minimum launch costs to LEO and GEO and a joint use of the ground-based installation to beam low cost power to "orbiting industrial parks".

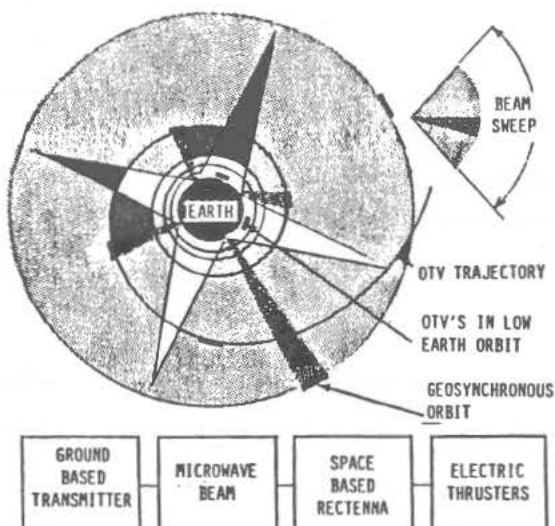


FIG. 1. LEO to GEO Electronic Transportation System

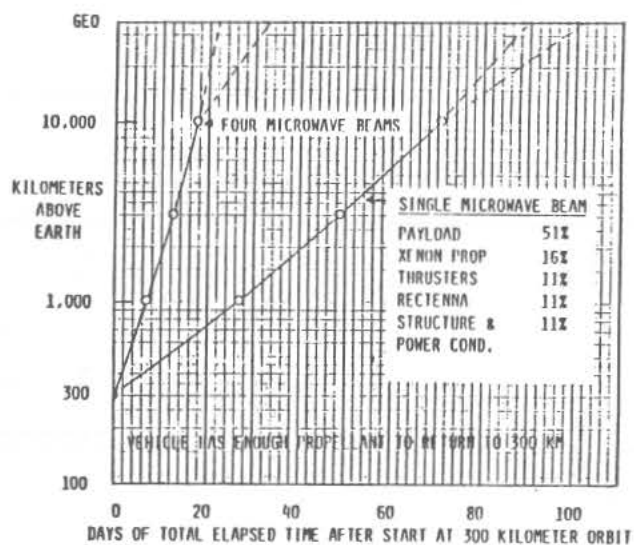


FIG. 2. Orbit Altitude as a Function of Elapsed Time

**LEO to GEO flight times.** The low combined mass of the ion thruster and the microwave receiver relative to the thrust generated allows large, unanticipated accelerations of an electric OTV. LEO to GEO flight times of about 10 days can be projected for an express (small payload) mission, after making allowances for initial intermittent contact with the microwave beam. Figure 2 shows the transport times for single and four beam systems for a 51% payload. (2)

**Technology readiness and modular construction.** The technologies of both the space portion (ion thrusters and "rectenna") are well developed but their interfacing needs experimental study. Modular construction allows easy expansion of both space and ground systems. Many low-cost microwave components are available.

**System capacity and costs.** A full scale system (4 beams and 4 OTVs) could handle up to 60,000,000 kg/yr of payload to GEO. Costs for 60 cycle earth power and 10 yr. system amortization cost, on basis of \$/kg of payload, are each estimated to be \$15/kg for a full scale system. Smaller systems will cost more but are still very attractive.

**Reduction of propellant mass.** The amount of ion thruster propellant needed in LEO for a typical round trip to GEO with payload is typically less than 10% that of propellant for conventional chemical rockets. Argon or xenon may be used.

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(2) W. C. Brown. Science Technology Series, Vol 67, 1987 Amer. Astro. Soc.

EVA CONCERNS FOR A FUTURE LUNAR BASE; Ann L. Bufkin,  
Terry O. Tri, and Robert C. Trevino, NASA/JSC

This paper presents an overview of extravehicular activity (EVA) issues and concerns for a future Lunar Base (LB). A top level description of the physical and operational make-up of the LB is included in the context of a first mission to begin build-up of the base. When completed, the base will support a crew of 12, with most supplies still coming from earth. The first mission of our scenario involves the set-up and activation of a separately landed construction center (mini-base) and preparation of landing areas for future missions. Many of the tasks that will be required for the full size LB are accomplished on this first mission, but on a smaller scale. A listing of representative EVA tasks is included, which describes possible activities of the first and future missions. The main areas discussed are extravehicular mobility units (EMU's) and EVA tools and equipment. Also, autonomous systems are briefly discussed, as they can lower mission risks by considerably reducing the amount of EVA. Attention is focused on several critical problems in these areas:

- 1) The lunar dust problem was one of the most troublesome for the Apollo missions and will be a major obstacle for all operations at the LB.
- 2) LB systems and components will not return to earth for repair, therefore designs must be reliable or easy to work on and repair.
- 3) The mechanics of working in one-sixth the earth's gravity must be studied completely in order to understand the limits of package size and weight to be moved by hand or other means.
- 4) The radiation levels at the LB will be higher than at Space Station due to the lack of radiation belts around the moon.

Recommendations are made for trade studies and technology developments needed to advance present capabilities to a usable level for LB.

**THE ROLE OF PHASIC ENVIRONMENTAL CONTROL IN LUNAR FOOD PRODUCTION EFFICIENCY: ARCHITECTURAL IMPLICATIONS.** Bruce Bugbee and Frank B. Salisbury, Plant Science Department, Utah State University, Logan, UT 84322-4820.

Phasic environmental control means that environmental conditions in a Controlled Environment Life Support system (CELSS) would be individually tailored for separate phases of a food-crop life-cycle. This concept is unique to controlled environment agriculture because, with the single exception of photosynthetic photon flux, environmental parameters in controlled environments can be altered with minimal increases in input costs.

Phasic environmental control may have enormous benefits for food production efficiency, but different environments cannot be created during a crop life-cycle unless a lunar-based CELSS has an appropriate architectural design. This paper reviews some of the biological benefits and engineering costs associated with phasic environmental control.

The relatively long life-cycles (30 to 240 days) of crop plants can be separated into distinct categories. The type and length of these categories varies for different crop species but several aspects are common. Our studies on wheat have led us to separate its life cycle into the following categories:

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Developmental Stage	Day Number (age)	Associated Morphological Change
1. Germination	0-3	Radicle and shoot emergence
2. Vegetative growth	3-12	Early leaf growth and root development
3. Reproductive Initiation	13-18	Microscopic change in apical meristem that determines ultimate spikelet number per spike
4. Extension	19-40	Determination of florets per spikelet
5. Anthesis	41-45	Pollination and fertilization
6. Grain Fill	46-80	Translocation of assimilates into developing seed

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We have found, for example, that temperatures that are suboptimum for photosynthesis, promote fertilization and seed set. If air temperature was reduced during the four days of anthesis, seed set and harvest index could be improved without greatly compromising growth rate.

We anticipate that phasic environmental control will be necessary to precisely balance source strength (photosynthesis) with sink capacity (edible tissue). Elevated CO<sub>2</sub> levels in a CELSS enhance photosynthesis and changes may be necessary to similarly promote sink development.

The use of phasic environmental control may mean that separate chambers and separate hydroponic systems would be necessary for each crop. An increased production efficiency would need to outweigh this design constraint.

CONCEPTUAL DESIGN OF A LUNAR BASE FACILITY; Corinne Buoni, et al., Battelle Columbus Division, Columbus, Ohio 43201

The transition from an early outpost to a permanently occupied lunar base will require extensive facilities and support systems to support the long term goals of self-sufficiency, scientific advancement, and resource exploitation. In many cases, these lunar support systems will benefit from the technologies and hardware employed in the Space Station era. In other cases, however, technologies must be further advanced and incorporated into systems for unique lunar applications, such as resource mining and processing.

This paper presents the preliminary results of a study which defined a preliminary facility concept to accommodate lunar support needs. Based on the lunar base mission requirements, several candidate science and application mission scenarios were developed and evaluated. These baseline missions, documented in a missions data base by Battelle, were used as a basis to select an array of missions for several discipline-oriented facilities. For each major facility, architectural drivers were identified (e.g., power, technology status, construction techniques, etc.) and incorporated into top level trades analyses. These analyses investigated facility accommodation options and capabilities in light of the mission requirements. A preferred configuration was selected and the physical characteristics and support requirements (e.g., power, construction, operations, servicing) were identified. This paper presents the results of one of the three facilities studied.



MICRO-ARCSECOND ANGULAR RESOLUTION FOR OPTICAL ASTRONOMY. B. F. Burke,  
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A lunar base offers the opportunity to establish a new generation of optical instrument: an aperture-synthesis array of telescopes that would be able to approach an angular resolution of a microarcsecond. At that resolution, a wide variety of new astronomical problems become accessible. The technical means are now under development on Earth, but there are fundamental limitations imposed by the Earth's atmosphere that will require removal to a space environment for high resolution of inherently faint celestial objects. Orbiting observatories probably will allow the achievement of angular resolution in the 0.1 to 1.0 milliarcsecond range, but beyond that the structures probably become too expensive and cumbersome. The Moon then becomes the ideal platform for the following generation of instrument. The dimensions of the array would be on the order of one hundred kilometers. None of the technical problems appear to be insurmountable, and the existence of skilled people to assemble and service the facility should be a substantial and probably vital contribution to making such an instrument a reality.



RADIO INTERFEROMETRY ON THE MOON; J. O. Burns,  
The University of New Mexico

The Moon is a nearly ideal location from which to perform astronomical observations. Its airless environment is well suited for diffraction-limited imagery at optical, infrared, and radio wavelengths. The lack of an atmosphere to scatter and delay electromagnetic waves, and the geological stability of the surface to maintain highly accurate baselines serve to make the Moon an excellent location for interferometry. In this talk, I will discuss the general role that radio interferometry may play on future lunar base observatories. In particular, millimeter and submillimeter arrays of telescopes could perform high resolution, high phase-stable observations that are difficult or impossible (above 300 GHz) from the Earth. This would allow astronomers to study planetesimal rings; planet and star formation including accretion disks, bipolar outflows, cooling and collapse of protostars; protogalaxies beyond  $z > 1$ ; and small scale anisotropies in the 2.7 K cosmic blackbody background. At the opposite end of the radio spectrum, there are exciting possibilities for new discoveries at kilometric wavelengths. The low density of plasma surrounding the Moon permits observations at very low frequencies ( $< 1$  MHz) on the lunar far side, thus opening an entirely new wavelength window on the cosmos. Here one could study the magnetospheres of the gas giant planets and Mercury; the distribution of galactic HII (ionized hydrogen) in absorption; and old populations of electrons near active galaxies and quasars. The Moon could also serve as one or more stations for an ultralong baseline radio interferometer stretching between the Moon and the Earth. Resolutions of better than a microarcsecond are possible at centimeter wavelengths. With such an interferometer, one could study solar flares with 10-m spatial resolution, star spot regions on other stars to better understand the solar-stellar connection, the nuclei of active galaxies very close to the engine, and the proper motion of water-vapor masers in other galaxies to set firmer limits on the Hubble constant of Universal expansion.

ARTIFICIALLY-GENERATED ATMOSPHERE NEAR A LUNAR BASE;  
J. O. Burns, I. Fernini, M. Sulkanen, J. Taylor, and S. Johnson,  
The University of New Mexico

The principle attraction of the Moon as a site for an astronomical observatory is the lack of an appreciable atmosphere which permits diffraction-limited high resolution observations and access to very low radio frequencies. The natural sources of particles injected into the lunar atmosphere are at such a low rate that the transport mechanisms which are present can easily remove them. However, an important question to answer is whether the gas and dust injected into the lunar atmosphere by exploration and colonization could overwhelm their removal and lead to a significant contamination of the lunar environment. It is possible that a point can be reached where the exponential decay lifetime of the artificial atmosphere could be greater than hundreds of years. Observations of the lunar atmosphere during the Apollo flights indicated that the lunar atmosphere's density was doubled for a period of two weeks. Analytical calculations by Vondrak (1974, *Nature*, 248, 657) indicate that the natural atmosphere removal mechanisms (solar wind and thermal evaporation) could be overwhelmed by gas and dust generated by human activity near even modest-sized lunar bases. A vigorous base injecting 1 to 100 kg/sec of gas and dust can produce an atmosphere that is optically thick to ultraviolet light within a human lifetime. Such a loss of vacuum could also be detrimental to materials processing experiments, and cosmic ray/gamma-ray detection. We will describe more detailed analytical and numerical modeling of an artificial lunar atmosphere and the possible effects upon lunar base astronomy.

LUNAR MINING OF OXYGEN USING FLUORINE; D.M.Burt,  
Lunar and Planetary Inst., 3303 NASA Road 1, Houston, TX 77058

"Ore" is any rock that can be mined at a profit. In the context of lunar mining, "a profit" means something that can be extracted from the moon more cheaply than the cost of transporting it from earth. Terrestrial mining is generally concerned with the recovery of metals from ore deposits. Such anomalous concentrations have yet to be identified on the moon and there is good reason to believe that they will be much less abundant than on earth. Plans for lunar mining will therefore have to concentrate on the utilization of common rock types such as anorthosite, basalt, and pulverized lunar soils.

Terrestrial mineral processing takes for granted the presence of unlimited C, O, and H for heating, cooling, oxidation, reduction, dissolution, and transport. The lack of these volatiles, and of other indigenous chemical reagents, greatly restricts the options available for mineral concentration and processing on the moon. An implication is that lunar processing should initially concentrate on products such as ceramics that can be derived from relatively untreated rocks, or on metals such as iron-nickel alloy that are already available or easily recovered.

A unique and important aspect of lunar mining will be the extraction of volatiles, particularly oxygen, from lunar rocks. This oxygen will be needed for both propulsion and life support systems. I suggest that oxygen recovery could most readily be done by fluorination, using fluorine brought from earth. Cheap and readily available, fluorine is the most reactive element, yet it can safely be stored in iron or nickel containers or transported as stable fluorides. Among the halogens, it is the lightest and forms the strongest bonds; consequently its compounds are the least volatile. The compound  $\text{SiF}_4$  is however, volatile, and this property could be used in desilicating silicates or in concentrating silicon for solar cells. As compared with oxygen, fluorine forms bonds that are roughly half as strong, and melting temperatures of most fluorides are consequently low. Molten anhydrous fluorides can therefore be electrolyzed to metals and fluorine at relatively low temperatures, as in Al-manufacture via the Hall-Heroult process on earth. Furthermore, the fluoride ion is roughly the same size as the oxide ion and readily displaces it in fluorination reactions (two atoms of F are required for each atom of O released). This process has long been used to liberate  $\text{O}_2$  from rocks in stable isotope laboratories (using  $\text{BrF}_5$  as the fluorinating agent).

All fluorine used in lunar mining will have to be recycled. Fluorite,  $\text{CaF}_2$ , will be the most stable and abundant product of the fluorination of anorthosite or other calcic rock. Recycling schemes for fluorine should probably therefore be based on fluorite as the starting material (as it is for fluorine recovery on earth).

TiO<sub>2</sub> IN CRATER LE MONNIER. V. V. Busarev, V.V. Shevchenko, Sternberg State Astronomical Institute, Moscow University, Moscow 119899, USSR

The technique of remotely identifying lunar rocks with an elevated titanium content is being ever perfected. From calculated values of the energy of metal-metal electron transitions in ilmenite, a spectral range of the characteristic 0.5-0.6  $\mu\text{m}$  absorption band has been isolated, where the band is superimposed on separate transitions in the crystalline field in  $\text{Fe}^{2+}$  and  $\text{Ti}^{3+}$  ions<sup>2,4</sup>. This result is most convincingly supported by laboratory measurements of purified terrestrial ilmenite. Fig. 1 shows the reflectance spectra of 4 samples that had been extracted from a depth of 100 to 1250m in the northwestern part of the Ukraine. The chemical composition of the samples is almost identical, and TiO<sub>2</sub> content varies between 49.28 and 49.40 wt.%. Sample 2 contains a somewhat larger amount of  $\text{Fe}_2\text{O}_3$ , which accounts for the peculiarities of its spectrum.

Observational data<sup>5</sup> suggests the northeastern edge of the Mare Serenitatis, including crater Le Monnier, is formed by titanium-rich basalts. The age of these basalts is estimated to be not more than 3 billion years<sup>1</sup>. However, the age of basalts with high titanium content in the neighboring Taurus Littrow region at the Apollo 17 landing site is considerably higher, viz. 3.8 billion years.

Figure 2 presents the reflectance spectra of two regions in crater Le Monnier and of the Apollos 11 and 17 landing sites, obtained by us in the 0.386-0.758  $\mu\text{m}$  range with a resolution of 0.0048  $\mu\text{m}$ . The spatial resolution is 25km on the lunar surface. The observations were made in May 1987, in the Crimea with the Zeiss-600 telescope. Crater Plato was used as a standard region. The calibration was done using data taken by R. L. Younkin<sup>6</sup>. The landing site spectra and plot 2 in crater Le Monnier are similar in their main features. A comparison of these spectra with Fig. 1 indicates an elevated titanium content in the surface rocks of these regions. The systematic shift of Younkin's and our spectral data was corrected using of the Apollo 11 landing site spectrum, and the spectra were used to estimate TiO<sub>2</sub> content<sup>3</sup>. The TiO<sub>2</sub> content for the Apollo 17 landing site and for plot 2 in crater Le Monnier is estimated to be 13-18%. For plot 1 in crater Le Monnier, the value is only 1.9%. Plot 1, the site of the Lunokhod-2 operation, lies in a heterogeneous region as shown by a spectrozonal map of the southern part of Le Monnier (Fig.3). Plot 2 is displaced northeast of this site. High titanium lunar basalts exhibit on the average  $\text{Al/Si}=0.26$ , a ratio corresponding to very dark basalts. According to generalized data on chemical composition of lunar rocks, basalts with high titanium content have the mean ratio  $\text{Al/Si}=0.26$ . The Lunokhod-2 photometric studies have demonstrated that the surface layer (Plot 1) contains at most 10% of this material. Observations of the nature of the terrain along the Lunokhod-2 path by TV pictures have revealed that the regions whose brightness in the UV spectral region is higher than the brightness in the red spectral region by a factor of approximately 1.2 have many more stones and fragments (by a factor of 10). Regions with the same color characteristics are observed near Taurus Littrow. Consequently, it may be inferred that titanium-containing basalts in the region have originated earlier than the rest of surface material. Later they were flooded by lava flows and excavated from under the surface as a result of impact metamorphism in the form of stones and fragmentary material.

The authors thank Yu. G. Shkuratov, A. I. Ipatov, and A. E. Kudinova for their help in the data processing.

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V. V. Busarev and V. V. Shevchenko

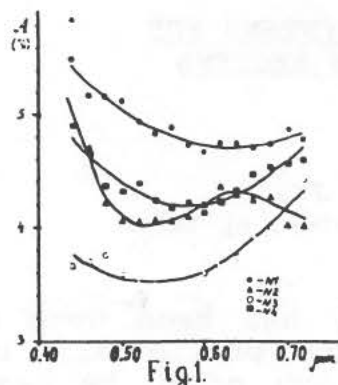


Fig. 1.

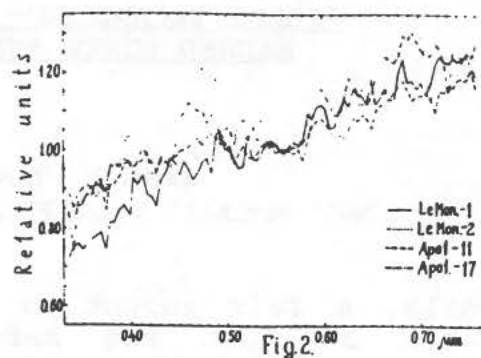


Fig. 2.

Fig. 1. The reflectance spectra of pure ilmenite samples. The average particle dimensions for different samples are: 1 -  $<0.5$   $\mu$ m, 2 -  $<0.25$   $\mu$ m, 3 -  $<0.5$   $\mu$ m, 4 -  $<0.1$   $\mu$ m.

Fig. 2. Reflectance spectra of lunar surface: Le Mon.-1 - plot 1 ( $\lambda = 30.7^\circ$ E,  $\beta = 26.2^\circ$ N) and Le Mon.-2 - plot 2 ( $\lambda = 31.1^\circ$ E,  $\beta = 26.3^\circ$ N) in crater Le Monnier, Apol.-11 - at the landing site of Apollo 11, Apol.-17 - at the landing site of Apollo 17.

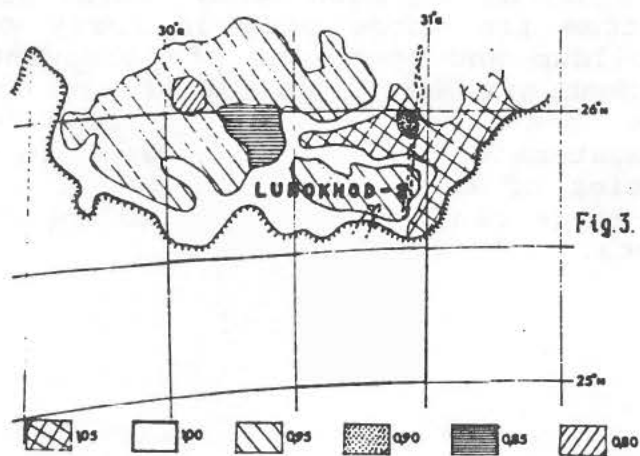


Fig. 3.

Fig. 3. Colorimetric map of Le Monnier(south). The areas with different color-indexes  $C(p(0.64 \mu)/p(0.36 \mu))$  are designated.

COMMON TECHNOLOGY AND SYSTEMS FOR  
MANNED LUNAR AND MARS SYSTEMS

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Recently, a fair amount of study has been done on manned missions to the Moon and Mars, and preliminary conceptual definition of some of the systems which might be used in the accomplishment of such missions has been done. These missions and systems span the spectrum fro those used in early exploratory phases to those for buildup and operation of permanently manned bases. Although, the Moon and Mars have significant differences in environment, there are many potential areas of common technology and common systems concepts in the elements envisioned for use in the vicinities of each of these bodies. This paper identifies areas where there can be common technology and systems concepts in such elements.



MINING FOR HELIUM - SITE SELECTION AND EVALUATION; E.N. Cameron, Wisconsin Center for Space Automation and Robotics, University of Wisconsin-Madison, 53706

Selection and evaluation of sites for mining helium on the moon, currently in progress at the University of Wisconsin-Madison (1), are based on four salient findings by various investigators of lunar samples:

1. Regoliths from areas underlain by highland materials contain less than 20 wppm He.
2. Regoliths of certain maria or parts of maria contain less than 20 wppm He, but others contain 25 to 49 wppm He.
3. The helium content of a mare regolith is a function of its composition. In particular, regoliths high in titanium are high in helium content.
4. Helium is concentrated in the -50  $\mu$ m size fractions of regoliths.

The first three findings focus attention on the maria as the most promising helium mining sites, more specifically on those maria underlain by high-Ti regoliths. Information on the distribution and extent of such regoliths is mainly from two sources: direct sampling by various Apollo and Luna missions, and remote sensing by gamma-ray spectroscopy (Apollo 15 and Apollo 16 orbiters) and earth-based measurements of lunar reflectance (2). Although only minute fractions of certain maria have been visited and sampled, sampling provides essential control on calibration and interpretation of data from remote sensing. Remote sensing indicates that Mare Tranquillitatis is the principal area of high-Ti regolith of the eastern nearside, but large areas of high-Ti regolith are indicated in Imbrium and Procellarum. High-Ti regolith found by the Apollo 17 mission in the Taurus-Littrow area is probably extensive but that area may be too heterogeneous for large-scale helium mining.

Recovery of significant amounts of He-3 may necessitate mining over areas of thousands or even tens of thousands of sq. km. Site selection must therefore be directed toward identification of large individual areas suitable for mining. The concentration of helium in the finer regolith fractions and considerations of ease of mining mean that mining areas must be as free as possible of blocks of rock and must also be free of sizeable craters. Pending additional lunar missions, information regarding these features must be obtained from lunar photographs and photogeologic maps. Photogeologic interpretation can shed light on another important question; namely, the uniformity of regoliths in various lunar maria. Spectral ratio mapping indicates that uniformity of maria regoliths cannot be taken for granted; e.g., such mapping indicates areas of intermediate-Ti regolith in Mare Tranquillitatis.

The present study is decidedly preliminary; available information is too limited to permit even a close approach to final evaluation. As a prelude to recovery of helium from the moon, systematic exploration and sampling of high-Ti maria should therefore have a high priority in future lunar missions.

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Cislunar Transportation: Technical, Economic and Societal Considerations

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A lunar base that can evolve from a research outpost to a major human habitation will require a space transportation system that can carry crew members and materials back and forth between low-Earth orbit and the Moon, and that can serve other cislunar destinations as well. The rationale for, and functions of an advanced space transportation system (ASTS) and operational requirements for these functions were defined, an architecture to meet the requirements and appropriate technologies identified and a phased technology growth path for the system projected. An economic model of cislunar transportation of lunar resources and flight mechanics of a comprehensive ASTS route network were developed.

Analysis indicated that there is a window of opportunity for the development of a lunar base and lunar resource utilization for large-scale projects. If the decision is made to utilize terrestrial materials for such projects, this action will result in a major build-up of investment in both terrestrial and near-Earth orbit industrial infrastructure. Once these investments have been made, even if subsequently shown to be less advantageous, the magnitude of sunk costs may make it less likely that a competitive cislunar infrastructure, including an ASTS and lunar processing facilities, would be developed until Earth-based investments had been amortized.

To accomplish the evolution of an ASTS capable of serving the widest possible range of missions, ASTS operational constraints were identified so that designs and technologies can be selected to mitigate identified constraints, the cost of mitigation measures established, and impacts on other users of cislunar space projected.

Key conclusions of the study are:

- o An early lunar program can develop a cislunar infrastructure if use of lunar resources will be economically justifiable.
- o Evolution of human habitations on the Moon can proceed if an ASTS will be safe and affordable, and if a lunar infrastructure has been developed and its costs amortized.
- o Development of an ASTS must be consistent with economic and societal criteria.

## DEPARTURE WINDOWS FOR ADVANCED EARTH-MOON TRANSPORTATION SYSTEMS

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This paper presents launch window availability for space transportation requirements associated with a lunar base. This includes Earth launch to orbit, transfer from low-Earth orbit (LEO) to low-lunar orbit (LLO), and transport to and from the lunar surface. The analysis focuses on space transportation as a system of nodes and vehicles, and it assesses the practicability of different transportation scenarios. The scenarios studied compare various system configurations and their sensitivities to departure window constraints, particularly for missions from low-Earth orbit to low-lunar orbit and the lunar surface.

The proposed Space Station orbit provides the baseline altitude and inclination for departure from LEO. Missions from LEO to the Moon are evaluated for launch opportunities and associated momentum changes ( $\Delta v$ ). The destinations for missions departing from LEO are low-lunar orbits ranging from equatorial to polar. The impact of different LLO altitudes and inclinations on the associated departure windows is analyzed for various vehicle types, and the results are compared on the basis of velocity increments required for orbital transfers and plane changes.

In addition to characterizing the departure windows for the individual segments of the mission (i.e., LEO to LLO and LLO to lunar surface), entire scenarios for delivery to the lunar surface at various latitudes are presented. These evaluations identify possible bottlenecks or traffic jams that arise for certain combinations of vehicles and infrastructure.

The additional velocity increments needed to rendezvous with a transportation node in LLO are calculated, and the departure restrictions imposed by docking with an orbiting node are compared with using an unconstrained parking orbit at the same altitude and inclination. This provides a means of evaluating the operational utility of a transportation node in LLO for its accessibility to the orbital transfer vehicle fleet. The availability of departure windows for descent from the various low-lunar orbits to the lunar surface is defined to ensure the viability of the transportation system as a whole. Return from the lunar surface to the orbiting facility is also addressed.

## MIXED-VEHICLE TRANSPORTATION FLEET FOR MISSIONS TO LUNAR POLAR ORBIT

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This paper details a cislunar transportation system for delivering payloads from low Earth orbit (LEO) to lunar polar orbit (LPO) using ballistic and low-thrust vehicles. Equatorial or near-equatorial lunar orbits severely restrict the access to certain parts of the Moon, particularly the higher latitudes. A polar orbit provides a greater level of accessibility to all latitudes on the lunar surface. The system described forms the link between the space station in LEO and a transportation node in LPO associated with an evolutionary manned base on the Moon.

Ballistic vehicles will be used to transfer cargo and personnel from LEO to LPO. Trajectories are analyzed to determine the frequency of launch opportunities and required velocity increments. Low-thrust vehicles will transport heavy cargos for longer duration, unmanned flights. Trajectories are presented for a continuous-thrust vehicle which is characterized in detail as part of the study. A fleet of low-thrust and ballistic vehicles capable of missions to LPO is presented as a result of the system integration analysis.

The lunar transportation node is fixed in a polar orbit to increase the availability of launch opportunities for orbital transfer vehicles and coverage of the lunar surface. The characteristics of the specific polar orbit selected, including the station-keeping requirements, are established. The constraints imposed by docking with a transportation node in LPO are also identified and presented. The entire transportation system described represents a possible scenario for supporting a manned lunar base.



**LUNAR BASE SURFACE OPERATIONS STUDY;** E. L. Christiansen, C. L. Conley, W. L. Davidson, J. K. Hirasaki, J. D. Overton, C. H. Simonds, W. R. Stump, and M. W. Dowman, Eagle Engineering, Inc., 711 Bay Area Blvd., Suite 315, Webster, Texas 77598. K. O. Fairchild, NASA Johnson Space Center, Houston, Texas 77058.

The purpose of this study was to perform an operations analysis on a human-tended lunar base. Specifically, the study (1) defined surface elements and developed mission manifests for a selected base scenario, (2) determined the nature of surface operations associated with this scenario, (3) generated a preliminary crew extravehicular and intravehicular activity (EVA/IVA) time resource schedule for conducting the missions, and (4) proposed concepts for utilizing remotely operated equipment to perform repetitious or hazardous surface tasks. The operations analysis was performed on a lunar base for a 6 year period of human-tended operation prior to permanent occupancy. The baseline scenario was derived from a modified version of the civil needs database (CNDB) scenario. It emphasized achieving a limited set of science and exploration objectives while emplacing the minimum habitability elements required for a permanent base.

Groundrules defined for the study include: (1) maximum lunar manned and unmanned cargo flight rates are assumed to build from 2 to 8 per year in the human-tended base period, (2) initial surface operations are based from a Manned Module attached to a lunar lander and are therefore limited in stay times to the life support capability of the lander's manned module, presumed in this case to be 8 days for 4 crew, (3) the center of operations shifts to the surface base and stay times for 4 crew are increased to 24 days after the following surface elements become operational: solar flare radiation shelter, habitation module, interface node, airlock, power system, thermal control system, and communications relay station.

Lunar base crew shift schedules were formulated from Shuttle guidelines and Space Station crew plans, and from them, time allocations for operational tasks were determined. For instance, of the 768 person-hours available on 4 crew, 8-day surface stay missions, only approximately 228 hours are actually available for surface operations after accounting for sleep, meals and personal time, spacecraft housekeeping and systems monitoring, arrival and departure spacecraft checks and preparation activities. Out of this 228 hour surface operations resource, 6 two person EVA's were planned to provide 72 hours of EVA operations. IVA maintenance and refurbishment activities required to support these EVA's consume 49 hours, yielding 107 hours for other IVA activities, such as teleoperation of base site surface preparation and construction equipment.

In addition, the study addressed specific surface operations in the following areas: IVA support activities for EVA, landing/launch site preparation, cargo handling equipment and activities, radiation shelter (buried module) emplacement, exposed module emplacement, construction equipment and operation, science operations, resource utilization operations, logistics and maintenance activities, human/machine division of labor, and contingency operations. For instance, the possible methods to provide 700 g/cm<sup>2</sup> of radiation protection (approximately 4 m of regolith overburden) for a solar flare shelter were surveyed and assessed, and the EVA/IVA time required for the baseline concept utilizing a bulkhead arrangement was determined.

Major conclusions of the study were that EVA/IVA schedule margins, particularly for early lunar surface missions, were small or negative, and that teleoperation of soil moving and construction equipment from Earth and the lunar lander was required to leverage limited EVA time resources, such as for site preparation and solar flare shelter emplacement. Also, a concept for a lunar surface telerobotic servicer was proposed to perform teleoperated inspection and maintenance activities.

# CONCEPTUAL DESIGN OF A LUNAR OXYGEN PILOT PLANT;

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A necessary step in developing the capability for full scale oxygen production at a lunar base is a small pilot plant to verify major process subsystems such as feedstock beneficiation, oxide reduction, and oxygen separation. The purpose of this study was to develop a conceptual design for a lunar oxygen pilot plant capable of producing 2 metric tons per month of liquid oxygen. A survey and evaluation of the various process pathways to extract oxygen was performed, including carbothermal reduction of ilmenite, hydrofluoric acid leach, fluorine exchange, carboclorination, and direct electrolysis of oxide melt. The feasibility of extracting solar wind hydrogen was also assessed.

A conceptual design was developed for a pilot plant based on reduction of ilmenite by hydrogen. Studies were conducted to define major process units and subsystems. A weight, power, and volume statement was produced. Pilot plant costs and impacts on lunar base operations were addressed. The costs and benefits associated with full scale oxygen production were also estimated. Conceptual design drawings and illustrations are included.



## CRISIS MANAGEMENT IN SPACE

**COLONIES - A HOLISTIC APPROACH;** Thomas M. Ciesla, Outer Space Environments, Spring, Texas 77388

Crisis - defined for present purposes as a state of events which result in conflict, anxiety, or fear - is omnipresent in space exploration. It may be said that life itself in space is a crisis situation, when man is completely dependent on his technology.

A space colony developed using a holistic approach is equipped to cope with the disruptive forces generated by externally or internally created crises. As a homeostatic micro-society, the space colony can then respond as a unified system capable of maintaining internal stability through the coordinated actions of man and environment. Figure One depicts a basic triad of holistic development in which each element is intrinsically tied to the others. In this simplified schematic the colony is divided into habitat, social dynamics and management structure. To achieve homeostasis the habitat, which serves as both home and workplace, is designed with the activities of the individual and the group in mind; attempting to circumvent the anxieties possible in an isolated and 'containerized' colony [2].

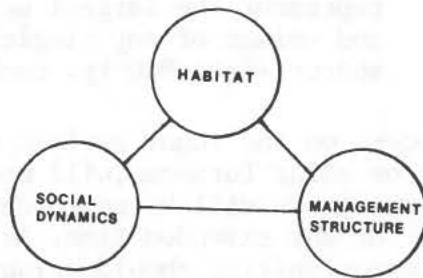


Figure 1.

A variety of subjects must be considered, from noise abatement and lighting, to music and earth broadcasts to help create a habitat that is acceptable for work and leisure time. Especially critical for long term missions are the issues of volume consideration and the need for privacy. Architectural tools to address these concerns must be incorporated to minimize stress and aggressive behavior. Space allocation for a sick-bay as well as a 'lock-down' area for possible psychotic crewmembers must also be examined for extended missions [1,3].

The categories of social dynamics and management structure incorporate the issues of work performance, small group interactions, moral, crew size and compatibility, leadership styles and emergency management procedures. Necessarily relying heavily on terrestrial based studies, the area of individual/group dynamics and the structure of management/authority will evolve the most as man moves into space on a permanent basis.

A holistic space colony then is one that allows the colony to exist as a homeostatic entity (man + technology + environment), minimizing irritating stimulus and is staffed with an adequate crew sensitive to the environment, each other and to the mission goals. Minimizing conflict between crewmembers allows mission planners and eventually the crew to concentrate on externally generated crises rather than internally generated events.

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### THE PROBLEM OF TRASH ON THE MOON ;

Thomas M. Ciesla, Outer Space Environments, Spring, Texas 77388

Extended human existence on the lunar surface will produce three basic types of waste: biological, atmospheric and manufactured.\* This study concentrates on the manufactured waste commonly termed 'trash'. To preserve the natural condition of the Moon and abide by the terms of various treaties that have been signed by the United States, a management plan must be considered prior to implementation of the first base camp.

**SOURCES OF TRASH.** Three major sources of trash can be identified: personnel activities; habitat construction/maintenance; transportation/surface activity. An analysis of the types of trash generated by each source is shown in Table One. A variety of materials will be represented in lunar trash, including paper, cloth, wood, plastics, ceramics and glass, aluminum and steel [3]. Of the items listed, the disposable descent platforms represent the largest weight and volume of any single source - at 4900 kg. each[1].

MAJOR CATEGORY	ITEMS GENERATED
PERSONNEL ACTIVITIES	PERSONAL HYGIENE ITEMS, FOOD CONTAINERS & CLEAN UP, LEISURE ACTIVITIES (i.e. paper, pens etc.)
ENVIRONMENTAL CONSTRUCTION & MAINTENANCE	EQUIPMENT PARTS, FILTERS, SUPPLY CANISTERS, SHIPPING DUNNAGE, NUCLEAR REACTOR SHELLS, MISC. CONSTRUCTION DEBRIS.
TRANSPORTATION/SURFACE TRANSPORTATION	DISPOSABLE DESCENT PLATFORMS, SHIPPING RESTRAINTS, PACKING MATERIALS, PROPELLANT CANISTERS, DISCARDED EQUIPMENT PARTS, FILTERS AND SUPPLY PACKAGING.

Table 1.

**DISPOSAL METHODS.** The primary disposal process on the lunar surface of the by-products of shredding [2], wet oxidation or solar furnaces, will be burial. The initial temptation of filling nearby craters will be unavoidable for the initial settlement, but cannot continue for any extended time. As lunar mining becomes a reality, ample landfill opportunities should arise. An alternative to crater filling or direct burial would make use of areas of perpetual shade if available near the colony. These areas, if large enough, exhibit absolute darkness and temperatures near 150° K that would make for excellent limited disposal sites.

Trash management practices must necessarily evolve as the space colony grows from the assumed 15 member crew, the infrastructure available determining exactly how the disposal will be handled, with minimum radiation exposure to the crew. Mission studies must address the methods of trash management early in the design process to provide the equipment and site logistics to handle what will be a growing problem [5]. The circling of early American Antarctic bases with a ring a garbage has shown us the importance of trash management in remote environments [4].

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\* Manufactured Trash defined here as any man-made item no longer useful.

## ASTRONAUT MISSIONS TO THE MOON AND MARS: A COMPARISON; Benton C. Clark, Planetary Sciences Laboratory (0560), Martin Marietta, Denver, CO 80201

The Moon and Mars are the solar system bodies most-often considered for man-tended outposts or permanently occupied bases. Commonality of purpose, hardware, and mission operations could, in principle, provide cost-savings and accumulating experience that would be applicable to both, but an analysis shows many differences as well.

**Science objectives.** Geologic exploration will be of high priority on both the moon and Mars. In addition to a much greater variety in styles of volcanism and the more likely possibility of contemporaneous volcanic or seismic activity, the martian surface has experienced eolian forces and apparently some or all of the effects of liquid water (catastrophic floods, channels, sapping, chemical weathering, sediment deposition) and ice (polar caps, permafrost, thermokarst, glaciation). Mars has an atmosphere, invoking investigations related to weather systems and climatology. A warm, wet paleoclimate leads to the possibility of extant life in oases or relics of extinct life forms (fossils). Mars also has two satellites that deserve thorough study.

Both the moon and Mars may be good locations for observational investigations, although the moon would be better for optical astronomy, cosmic dust collection, and Earth observation. Radio astronomy would benefit from a backside location on the moon; Mars would create a longer baseline for VLBI.

**Environment.** Thermal balance, one radiatively dominated and the other convectively dominated, is quite different at the two locations. Gravitational forces are three times higher on Mars. The martian atmosphere provides a minimum of  $16\text{-}26\text{ g/cm}^2$  shielding against radiation and meteoroids. The martian soil and atmosphere contain an abundance of light elements (especially, H, C, N, O, S) and includes both  $\text{CO}_2$  and  $\text{H}_2\text{O}$ , the ingredients necessary to grow plants. The moon is impoverished in the light elements, except for O bonded in silicate minerals (which could be used to manufacture lunar oxygen, LLOX). Production of metals would probably be quite different on the two bodies because of the apparent availability of salts on Mars, compared with the required use of igneous rocks on the moon. Hydrogen peroxide and other valuable H-containing commodities can be manufactured on Mars, but not on the moon.

**Engineering systems.** Propulsion systems for primary access to the moon and Mars may be significantly different. Multiple heavy-lift launch vehicles (HLLVs) will be required just to depot propellant for the Mars mission, but LLOX availability would reduce this load (except for maintenance of the LLOX manufacturing infrastructure). Mars missions require long-term cryo-storage (up to 1.5 yr.) in Mars orbit. Ascent vehicles might be similar, but descent vehicles will not because of the anticipated use of aerobraking and parachutes at Mars. Likewise, orbital insertion will very likely employ aerocapture at Mars but can only be by retro-propulsion at the moon. Different Earth-based communication hardware systems are expected for the two missions because of major discrepancies in bandwidth feasibility. Fission reactors can be vacuum rated (ala SP-100) for the moon, but would be of different design for the martian surface. Life support systems for Mars would have to be much more power conservative, but habitats on the moon will require much greater wall thickness. Spacesuits and EVA operations will be different in the two locations because of the weight differential and exposure hazards.

**Operations.** The round-trip propagation time for communications to the moon is 3 seconds; for Mars, it ranges from 16 to 40 minutes. Control of lunar operations can be Earth-based, as in the past; for Mars, the style of mission operations will be entirely different and require greater autonomy for the crew. On the martian surface, a 24.66 day/night cycle would dictate most operations and be desynchronized from the day/night at mission control on Earth; on the moon, the astronauts will have to cope with the long lunar night. The isolated and confined environment of a Mars-bound crew is quite different in intensity; rescue for stranded Marsonauts is mostly out of the question. The number of Mars astronauts needed per decade will be about an order of magnitude below that needed for Space Station and Lunar Base. Solar flares can be monitored from the Earth for lunar missions, but require sophisticated on-board instrumentation to provide similar monitoring during much of the Mars mission.

**National goals.** International cooperation could occur in either case, but is more often invoked for the more ambitious and politically neutral Mars missions. The moon can serve as an Earth-monitoring base and a nearby LLOX supply. Mars missions require extensive Space Station operation and involvement, including zero-g countermeasures development, spaceship assembly, and in-space fuel handling.

Colonization is possible on Mars because of the availability of natural resources. Going to Mars would be the first step into deep space, outside the gravitational influence of the Earth.

## Earth Moon Bridge

E. Clifton, R. Gross, S. Durst, and J. Miller

Lunar Entrepreneurs Corporation  
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The paper to be presented will attempt to explain and justify the thesis that free enterprise can successfully develop and profitably operate an Earth Moon mass transportation system and consequent lunar civil facilities. It will describe a plan that anticipates returns to individual stockholders worldwide that include monetary profits, transportation and other rights, and privately secured lunar acreage in the form of homesteads, mining claims and other.

The basic tenet of the plan is that the greatest returns from space enterprise will be fundamental individual and corporate rights; including but not limited to freedom, equality, liberty, justice, health, prosperity, self definition and fulfillment, and happiness. It would offer to peoples of all constellations the opportunity to acquire the attributes of life in a new environment, unfettered by the obligations and constraints associated with terrestrial cultures.

The plan is in effect an experiment to be carried out by the Lunar Entrepreneurs Corporation, incorporated 20 July 1987. The experiment may demonstrate: 1) That a private company can successfully finance, construct, and operate a cislunar mass transportation system by 1992 - 1996; 2) That the system and follow-on facilities can return a fiscal profit to terrestrial investors; and 3) That the human society established on the Moon and in free space can take hold and grow, largely independent of the Earth.

Long-range (10-20 year) profitmaking activities will be forecast including revenues from sales of transport tickets, lunar minerals, orbital and lunar facilities, lunar property rights, space-derived electric power, cislunar spacecraft, delta vee and fuel. Near-term income generating mechanisms (in addition to traditional equity and debt offerings) will include many of the above, and are also expected to take the form of cooperative endeavors with other lunar-oriented organizations. A Lunar Entrepreneurs Freemarket Exchange established beyond the confines of Earth is one proposed enterprise. A smaller, but perhaps more immediately pragmatic project, is a Private Lunar Polar Ice Search.

The Lunar Entrepreneurs Corporation will overview its intentions to accommodate as partners all able and willing lunar entrepreneurs and enterprises which wish to share in the challenges and rewards. The paper concludes that a cooperative approach by private, government and international interests is more than a sufficient means to establish a cislunar infrastructure -- it is probably the best way.



## NUCLEAR-OXYGEN REACTION SYSTEM FOR LUNAR OPERATIONS

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**PROBLEM:** Plans for the establishment of a manned Lunar base, of 12 to 20 people, require that hundreds to as much as a thousand tons of liquid propellants be delivered to Lunar orbit and the Lunar surface yearly. The annual cost to deliver this much fuel would be about one billion dollars for each fifty tons of fuel delivered. This is prohibitively expensive.

**SOLUTION:** Deliver two nuclear rocket engines to Luna, one to the surface, one into low Lunar orbit. The surface engine, complete with liquid oxygen tank, cargo hold, landing gear, and avionics would weigh about eleven tons. The engine in LLO equipped with a space radiator, to dissipate decay after-heat, would weigh about six tons. Together they could be delivered to their destinations by a single shuttle derived heavy launch vehicle. The rockets would use oxygen, produced as a by-product of various mineral separation operations on the moon, for reaction mass. These nuclear rockets would not only eliminate the need for almost all fuel to be delivered to the Lunar surface and LLO, they would make possible much larger operations both on the Moon and in cislunar space.

**OBSTACLES TO SOLUTION:** The main obstacle is the extremely corrosive effects of high temperature, high pressure, pure oxygen on rocket engine components. There is also difficulty matching suitable engine core lining material with core fuel and matrix material.

## PERFORMANCE TABLES FOR HIGH, LOW, AND INTERMEDIATE PERFORMANCE NUCLEAR ROCKETS

	LOW	INTERMEDIATE	HIGH
ENGINE NOZZLE EXHAUST TEMPERATURE, KELVIN	1920 degrees	2240 degrees	2616 degrees
ENGINE Isp	185	200	216
ENGINE IDLE TEMP. K	1000 degrees	1000 degrees	1000 degrees
OXYGEN TANK CAPACITY		590,000 pounds (268,180 kilograms)	
F/W RATIO	15	16	17
PAYLOAD IN 25 MILE CIRCULAR LLO	125,000 pounds	140,000 pounds	160,000 pounds
ENGINE WEIGHT		10,000 pounds (4,550 kilograms)	
PROPELLANT TANK, LANDING GEAR, FRAME, AVIONICS, ETC.		9,000 pounds	
RESIDUAL LO <sub>2</sub> ON LANDING (FOR REACTOR DECAY HEAT AFTER-COOLING)		4,000 pounds	
REACTOR POWER	552 MW	750 MW	1,000 MW
THRUST	148,000 LB.	160,000 LB.	172,800 LB.

**A PRELIMINARY SURVEY OF LUNAR RILLES: THE SEARCH FOR INTACT LAVA TUBES;** Cassandra R. Coombs and B. Ray Hawke, Planetary Geosciences Division, Hawaii Institute of Geophysics, University of Hawaii, Honolulu, HI, 96822.

Sinuuous rilles are a common feature on the lunar surface. Formed during the eruption of basaltic lavas, the rilles may have evolved into lava tubes when segments of the channels roofed over. Quite common in terrestrial basalt flows<sup>1</sup>, basaltic lava tubes may have also formed on the Moon. Although they are an order of magnitude larger than their terrestrial counterparts, lunar sinuous rilles and their associated lava tubes may have remained intact since their formation millions of years ago. The use of intact lunar lava tubes has been suggested as a possible locality for the lunar base.

Horz<sup>2</sup> noted that lava tubes are ideal for housing the lunar base in that they: 1) require little construction: a pod may be placed inside with a minimum amount of building or burrowing; 2) provide a natural environmental control for "intra-" and "extra-pod" work; 3) provide protection from the natural elements (i.e.: cosmic rays, comet and asteroid impact, secondary cratering debris); 4) provide an ideal natural storage facility for "extra-pod" vehicles and machinery. This study identified several possible intact lava tubes that could be used for housing a lunar base.

A survey was made of available Lunar Orbiter and Apollo photographs for possible intact lava tubes using: 1) specifications determined by Oberbeck *et al.*<sup>3</sup> (i.e.: max. channel width-385m; min. roof thickness-65m); 2) usefulness of the locality for the lunar base. We looked for a site with easy access to all parts of a region (i.e.: near prime ore deposits, near a limb, possibly near a mountain range for added protection and future burrowing); 3) whether or not the site was readily available for pod placement. We looked for sites where little or no degradation had occurred (i.e.: few impacts, slumping); and, 4) location of rille/tube in a relatively flat region for greater ease of mobility during "extra-pod" activities.

At the dimensions specified by Oberbeck *et al.*<sup>3</sup> for a stable roof, the tubes/rilles are barely discernible in the currently available Apollo and Orbiter photographs. However, several areas of great potential for rilles with tubes of these dimensions have been located. Some of these areas include: 1) Eastern Procellarum (IV 158-H2); 2) N of Aristarchus (IV 151-H1, IV 151-H3); 3) west of Plato (IV 134-H3); 4) N of Braley (IV 138-H3); 5) N of Tobias Mayer (IV 133-H2); 6) S of Lalande (IV 114-H1); 7) NW of Prinz (IV 144-H3); 8) Alpine Valley (V 102-H); 9) S. of Herodotus Kappa (V 209-M); and 10) Marius Hills Region (V 212-M).

In summary, this preliminary survey of existing Apollo and Orbiter photographs has illustrated the likelihood of finding an ideal intact lava tube. The use of higher resolution photographs and the construction of topographic and orthotopophotomaps for these regions will help to further identify and/or confirm the existence of these lava tubes.

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IMPLICATIONS OF THE NASA LUNAR INITIATIVE FOR A TYPICAL SPACE TRANSPORTATION ARCHITECTURE; Bruce Cordell, General Dynamics, Space Systems Division, San Diego, CA; Lee Varnado, NASA/MSFC; Collin McClain, General Dynamics, Space Systems Division, San Diego, CA

As part of the Space Transportation Architecture Study (STAS) for NASA/MSFC, we have developed concepts for a space transportation architecture that optimally capture the government baseline space mission model. We have identified and studied the modifications of this architecture that would be required to support the establishment of a lunar base as envisioned by NASA in its Lunar Initiative. Some effects of lunar oxygen production and advanced propulsion on architecture costs and vehicle use have also been identified and investigated.

We have performed an analysis of the most useful and efficient mission alternatives for Earth-Moon transportation, including near-Moon operations. Our analysis and results were aligned with the Lunar Initiative mission model provided as part of STAS by NASA. This model includes the establishment of a Lunar Orbit Service Station in low lunar orbit (LLO) in 2005. Prior to this, an expendable lunar lander and ascent vehicle are utilized for personnel and cargo missions. After 2005, a reusable lander operates between the lunar surface and the LLO and lunar oxygen is assumed to be available in LLO. The major elements of the lunar oxygen plant are delivered to the Moon between 1999 and 2003. Our mission analysis and the lunar mission model data were then utilized in our Transportation Analysis Program (TAP) which determines the most cost-effective vehicle combinations to perform the lunar missions.

We examined two lunar oxygen approaches: 1) lunar oxygen is produced on the Moon and transported to LLO resulting in between 60 and 70 KLB/yr of lunar oxygen being available after 2005 (this is sufficient for escape from LLO for the vehicles in the lunar mission model), and 2) sufficient lunar oxygen production so that the Orbital Transfer Vehicles (OTV) are refueled only at LLO, with the excess lunar oxygen being returned to and stored at LEO.

We evaluated one advanced propulsion system for the lunar transportation system: nuclear-electric propulsion (NEP). This vehicle generates 3 MW of electric power for use with the xenon-fueled electrostatic ion thrusters which have an  $I_{sp} = 5000$  s. Assumptions about system parameters are consistent with current projections of technology for the post-2000 timeframe. Performance and cost sensitivities with respect to vehicle dry weight and vehicle life were performed.

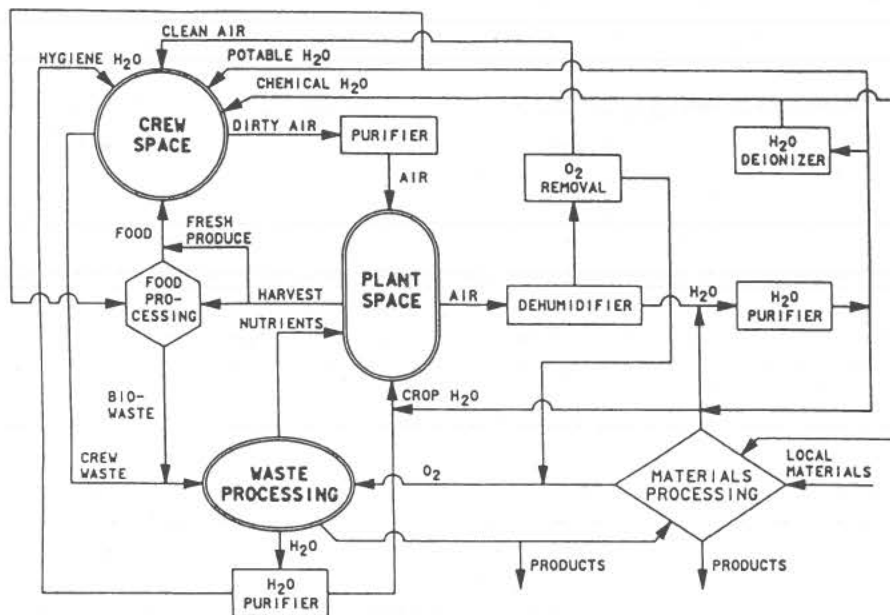
Our conclusions include: 1) the Lunar Initiative mission model has relatively little impact on the General Dynamics baseline space transportation architecture; 2) although in our recommended architecture the Space-Based Reusable Orbital Transfer Vehicle (SBROTV) was optional, we recommend that the IOC for the SBROTV be in 1999 due to the lunar manned missions; 3) the cost effectiveness of lunar oxygen (based on life cycle cost analyses) used to support the lunar transportation architecture appears to be marginal-to-promising depending on which assumptions (e.g. relations between plant productivity and mass) are utilized; and 4) the use of a large (3 MW) nuclear-electric propulsion vehicle for delivering cargo between LEO and LLO has propellant advantages but costs are highly sensitive to DDT & E, vehicle dry weight, and vehicle life.

PROJECT "HOME" (HABITAT OVERMATCHING THE MOON ENVIRONMENT)  
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Project HOME (Habitat Overmatching the Moon Environment) is introduced as a habitat of a dozen human crew for long-term residence on the moon. This paper describes the habitat development scenario based on risk analysis and reliability techniques.

Unpiloted missions are projected to be necessary for lunar habitat preparation to assure long-term human presence. The scenario developed for HOME is characterized by lunar operations before crew arrival and assurance of safe haven for human survival. The scenario will be described in terms of the major elements of a closed loop life support system. Food production and reservoirs of life support materials including food will be related to the integrated life support reliability and risk control.



CLOSED LOOP LIFE SUPPORT MAJOR ELEMENTS

6371. ART, 3

# LUNAR CONCRETE FOR CONSTRUCTION

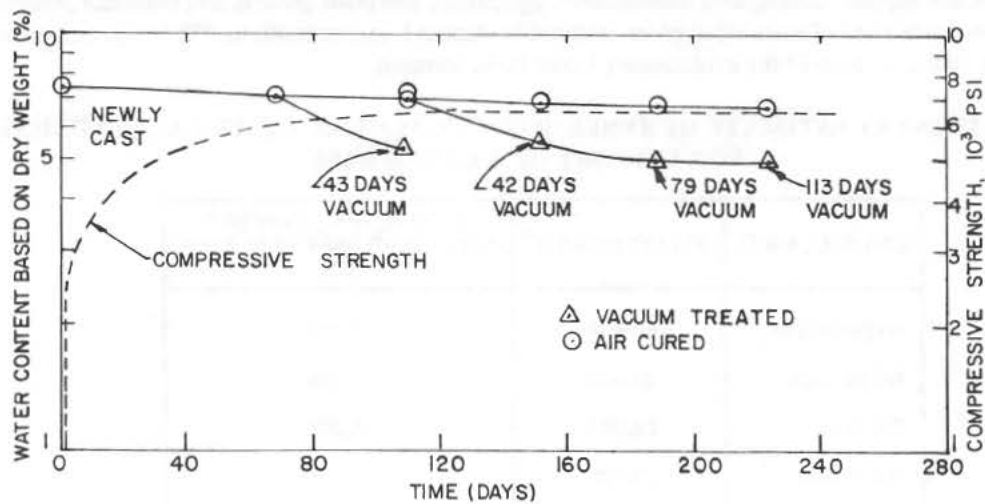
H. S. Cullingford\* and M. D. Keller\*\*

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Use of concrete has been proposed for lunar base construction needs. This paper will extend authors' experimental data on compressive strength and outgassing of concrete in vacuum for lunar applications.

Effects of vacuum on concrete were studied by the authors. Concrete was found stable in vacuum with no deterioration of concrete quality as measured by its compressive strength. Based on existing data, concrete might be a suitable material for long-term lunar structures. Innovative concrete making processes such as "preplaced" aggregate concrete, "closed loop" curing apparatus, encapsulation by foils and films are recommended here on the moon. An experimental program is also outlined for implementation.



EXPERIMENTAL DATA

# SYNERGISM OF HE-3 ACQUISITION WITH LUNAR BASE EVOLUTION;

T.M. Crabb and M.K. Jacobs; Astronautics Technology Center, Madison, WI

As today's technology advances toward development and commercialization of space, the permanent settlement of the Moon becomes a valuable means for extraterrestrial exploration and exploitation. Major factors for the feasibility of establishing a permanently manned Lunar Base include space transportation requirements, mass required at the Lunar surface, logistics/resupply requirements, and commercialization potential. This paper identifies requirements of an evolutionary Lunar Base scenario and impacts of mining He-3 on normal Lunar Base operations. He-3 is used in a D-He3 fusion reaction and is not found in significant quantities on Earth. Initial estimates show that available quantities of He-3 on the Moon can provide the equivalent of 40,000 years of the U.S. electrical power generation demand recorded in 1985.(1)

The evolutionary Lunar Base scenario consists of four phases: a man-tended science base supporting 4 to 6 crew members; a manned science and technology development base with small scale mining operations supporting 4 to 6 crew members; a 10 man science and manufacturing base with expanded mining capabilities and increased exploitation of Lunar resources; and a 15 to 20 man base supporting full scale mining activities and Lunar resource exploitation with the potential for exportation of Lunar resources for support of other space operations to relax requirements of Earth deliveries. Each phase is described by three major systems: the science system which performs experiments relating to geology, life sciences, astronomy, energy systems, and technology development; the manufacturing and production system which includes mining operations and Lunar resource utilization schemes; and an infrastructure/support system which provides habitats for life support, launch and landing facilities, and power for overall Lunar Base operations.

Lunar He-3 supplies originate from solar winds that are embedded in the near surface regions of fine grained Lunar regolith particles. Operations required to obtain He-3 encourage the collection of other valuable volatiles available from the solar wind gas mixture with relatively small mass and power penalties. Other constituents of the solar wind, H<sub>2</sub>, H<sub>2</sub>O, CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>, can be used to resupply Lunar Base subsystems such as transportation, life support, atmosphere maintenance, agriculture and plant growth, and chemical processing. The table below shows quantities of solar wind gases released by heated Lunar regolith to 750 C and quantities of these gases required by the last phase of the evolutionary Lunar Base scenario.

**PRELIMINARY ESTIMATE OF SYNERGISTIC POTENTIAL OF HE-3 ACQUISITION  
FOR SUPPORT OF A LUNAR BASE**

GAS RELEASED	KG / 10 KG HE-3 *	ANNUAL REQUIREMENT FOR LUNAR BASE RESUPPLY (KG)
HYDROGEN	69,000	17,700
NITROGEN	20,000	300
CARBON	74,000	45,000
HELIUM-4	33,000	

\* Predicted initial He-3 production = 13 - 15 kg He-3 per year

Preliminary calculations show that these solar wind gases collected during He-3 mining could reduce the resupply requirement for a Lunar Base by approximately 8% for one kg of He-3 obtained. Other considerations used to assess synergistic potential of He-3 acquisition include commonality of hardware, shared infrastructure, and transfer of technologies developed. Impacts of He-3 mining operations on transportation requirements, base logistics, and commercialization potential are shown.

## References

(1) Kulcinski, G.L.; Santarius, J.F.; and Wittenberg, L.J. (1986) Lunar Development Symposium

## A BIOREGENERATIVE LIFE SUPPORT SYSTEM FOR A LUNAR BASE

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The establishment of a permanently manned Lunar Base will benefit greatly from the development of a bioregenerative life support system that is capable of substantially reducing the resupply needs over physical chemical, regenerative life support. This paper describes one possible configuration of a Controlled Ecological Life Support System (CELSS) that could support a manned Lunar base.

A CELSS concept is based on the fact that plants can convert solar energy through photosynthesis to produce food and oxygen and to absorb carbon dioxide. Also, the water transpired by these plants can be condensed and used as a potable water supply. Many of the nutrients required by these plants can be produced from treated waste products which aids in further reduction of resupply mass. The natural Lunar environment and available Lunar resources may be integrated into the CELSS to reduce its system and resupply mass. The preliminary concept presented in the paper has been divided into major subsystems as follows:

- Enclosures and System Integration
- Irradiation
- Nutrient Supply
- Temperature/Humidity Control
- Atmospheric Circulation
- Plant Culture Support
- Harvesting/Transplanting
- Sanitation
- Atmospheric Constituent Control
- Waste Processing

System mass, resupply mass, and power/thermal requirements are addressed for each subsystem. These estimates were then compared to the same requirements of a water-and-oxygen-closed, physical chemical life support system.

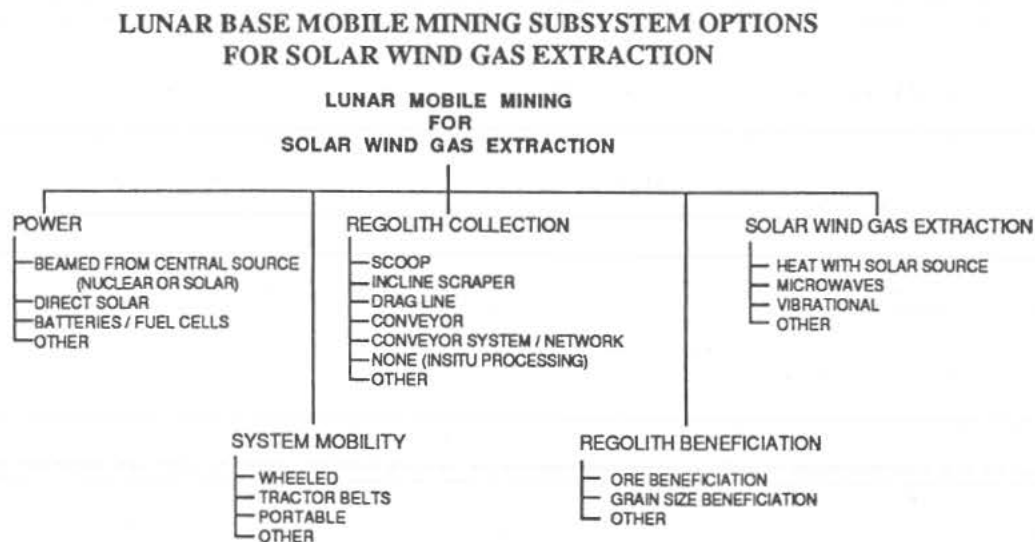
Preliminary calculations show that the CELSS has an initial launch mass an order of magnitude higher than the standard physical chemical life support system. However, the resupply needs are much lower for the CELSS thus creating a "payback" time at which the physical chemical initial launch mass plus its resupply equals the initial launch mass of the CELSS plus its resupply. This payback time was found to vary with crew size with decreasing time to payback for increasing crew size. Payback for the Lunar CELSS is estimated at about a decade for a full crew. Based on a typical evolutionary Lunar Base scenario, implementation of a CELSS appears cost effective eight to twelve years after the initial Lunar Base is implemented.

Much of this work was done to support the Wisconsin Center for Space Automation and Robotics in the analysis of terrestrial and space commercial spinoff potential of various CELSS technologies.

**RESOURCE MODELING FOR DESIGN OPTIMIZATION: LUNAR BASE MOBILE MINER;** T.M. Crabb, M.K. Jacobs, and R.S. Schultz; Astronautics Technology Center, Madison, WI 53716

To assist the task of trade-off and sensitivity studies related to design optimization, Astronautics has developed a computerized methodology to predict direct and indirect resource consumption. The Resource Estimation and Tradeoff Analysis Model (RESTAM) consists of three major elements; a functional hierarchy, resource mapping functions, and a support resource iteration. These elements are used to estimate resource requirements from design subsystem performance parameters.

This paper describes the application of RESTAM to optimize the design of a mobile mining system for solar wind gas extraction. Solar wind gases such as hydrogen, nitrogen, helium and carbon are embedded in the near surface regions of fine grained lunar regolith particles and can be released by heating. The mobile mining system is comprised of five major subsystems; power, system mobility, regolith collection, regolith beneficiation, and solar wind gas extraction. Subsystem options are shown in the figure below.



Performance parameters are calculated for each subsystem option and entered into the modeler. Each mining system design configuration is represented by subsystem selections. The modeler calculates direct and indirect resource consumption based on the subsystem selections made by the user. Indirect resources are determined through iteration of direct support resources through a recursive matrix. Designs are optimized by altering subsystem selection to minimize overall resource consumption. Used in this manner, the modeler becomes a valuable analytical tool to assist in trade-off and sensitivity studies and to identify major design drivers relating to performance and support.



LUNAR SURFACE SYSTEM CONCEPTS - INITIAL LUNAR BASE PHILOSOPHY  
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Fundamental questions are posed concerning the nature of initial lunar base structures and surface transportation. Three alternatives are discussed for the construction of initial habitats and protective structures: (1) brick structures constructed from lunar regolith, (2) prefabricated structures lifted from Earth, and (3) tunnel type structures. Two alternatives are presented for surface transportation systems: (1) building roads, tracks, and mass driver type foundations, and (2) transporting all-terrain type vehicles or above surface vehicles from Earth which do not require surface transportation facilities.

A two-phase initial lunar base establishment procedure is discussed which includes an unmanned and a manned mission. It is suggested that the initial manned mission should include a prefabricated structure and an all-terrain vehicle as it has included in missions to date. The manned mission is used to evaluate the progress of the unmanned mission and perform maintenance, measurement, and construction tasks requiring manned presence.

Because rapid surface transportation is not needed in the early base development due to anticipated use of all-terrain vehicles and a limited manned presence, the building of roads, tracks, and mass driver type foundations can be accomplished over a relatively long period of time by using unmanned construction equipment. Both tunnel type facilities and brick structures have advantages and disadvantages. It is suggested that, in concept, brick can be made rather simply from lunar regolith, but that placement of clear spans which are both protective and of large areal extent is not simple. Tunneling solves the question of protective cover very nicely, but high seismic velocities are anticipated which makes tunneling by mole type excavation difficult. In all cases, techniques such as the Los Alamos rock melting technology are shown to be useful, but dependent upon development of suitable penetrators and suitable power sources such as improved RTG's and products of the SP-100 program.

DEFINING LUNAR BASE ACTIVITIES: THE MISSION SCENARIO DATA BASE - MSDB; Micheal A. Culp and Alan B. Binder, Lockheed EMSCO, 2400 NASA Rd. 1, Houston, TX 77058

Part of NASA's current effort to define the Lunar Base Program is the development of a Mission Scenario Data Base or MSDB. The purpose of this data base is to provide NASA with a complete list of the activities (and support requirements) which can be carried out as part of the program. The MSDB will be used to develop and evaluate various Lunar Base scenarios.

As an example, one scenario will certainly be that the base will support lunar science and resource exploration. Such a scenario will be developed by choosing a number of activities from the MSDB and laying out a time sequence for them. One might suggest that petrological and selenochemical laboratory facilities should be set up at the base, while a network of seismometers, heat flow probes, magnetometers, etc. is being deployed by unmanned landers. As these activities are completed, sample collection for analysis at the base and surface exploration might be initiated by sending out crews on long traverses in pressurized rovers. Further, these crews might be resupplied and rotated by sending manned landers in 2 month intervals to the rovers, etc.

The MSDB will contain the rationale behind each of the individual activities, as well as their primary man power-, equipment-, life support-, electrical power-, etc. requirements. These data will then be used to define the total base requirement on a time dependent basis. This then will be used to define the space transportation requirements, etc. and finally the entire scenario will be evaluated and compared with others.

The development of the MSDB is not only important for the definition of the Lunar Base Program, but also to the individuals who are interested in using the Lunar Base. Simply put, every one who want to ensure that his experiments, etc. will be considered as part of the Lunar Base Program should see to it that his ideas, complete with all the support requirements, are communicated to the builders of the MSDB.

EVOLVING CONCEPTS OF LUNAR ARCHITECTURE:  
THE POTENTIAL OF SUBSELENE DEVELOPMENT

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STARNET STRUCTURES, INC

Successful development of the Moon depends upon man's ability to adapt himself to a new planet. Central to the adaptive process will be the architecture which we invent for the lunar setting. The architecture of lunar settlement must be considered as a vital subsystem interacting with and supporting the larger system of overall lunar development. As such, we should consider that the best and most appropriate lunar habitat designs are most likely to emerge from a process which responds to the requirements of the broadest possible range of disciplines.

With this in mind, the paper will begin by presenting a consolidated overview of many of the chief environmental design issues which are certain to shape lunar base architecture. Illustrations will be presented in order to demonstrate the nature of these issues clearly, and to suggest how they may be interrelated.

Of these issues, the authors will present three issues which they believe are likely to emerge as predominant and form-determining, and discuss them in detail. Specifically, the authors are concerned with the issues of spatial quantity, radiation shielding, and the ways in which political considerations may shape lunar base design, and the manner in which these three particular issues tend to interrelate. The basis for this discussion will be ongoing architectural research through which the difficulty of these issues has been noted:

The tendency to underestimate the importance of spatial quantity to lunar inhabitants must be considered. Human beings require space; exactly how much remains unknown. Engineering limitations with regard to long spans, atmosphere containment, and economics often provide an all too easy conclusion that lunar habitats must be small rounded boxes. The trustees of our expanding human civilization cannot be expected to live in maximum security igloos.

The use of mass, most often in the form of simply piled regolith, or modularized building units, as a shield against harmful radiation is well known, and is very often the basis of many of the proposed design concepts. Very often this results in designs which are either buried or which have superstructure building envelopes 3 to 5 meters thick. Here, the need for lunar superstructures is called into question.

Beginning with the very decision-making process and determination to go back to the Moon; continuing through considerations of property definition, economic standards, and governance; and ranging as well to the implications of multinational cooperation, it is clear that the architectural form and functional organization of lunar settlement will be in large measure a function of political considerations.

The paper will go on to discuss the potential of subsurface (subselene) development of the moon, showing through computer-aided illustration how subselene architecture might be implemented, and how the issues mentioned above would be considered and mitigated. The reader will be presented with a range of architectural illustrations and a discussion of the merits of subsurface and partial-subsurface development describing a hypothetical evolution of lunar-specific construction technologies, and the potential of architectural design on the Moon.

EARTH-MOON TRAJECTORIES WHICH UTILIZE A  
LUNAR MAGNETIC ACCELERATION DEVICE

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Transportation within the Earth-Moon system is one of the major obstacles to establishing a permanent manned presence on the Moon. Use of a lunar magnetic acceleration device (LMAD) greatly reduces the amount of propellant required by replacing rocket propulsion with electromagnetic acceleration for lunar launch and landing. This makes fully reusable single stage vehicles feasible for round trip transportation between Earth orbit and the lunar surface.

Primer vector theory is used to develop optimal, impulsive trajectories between Earth orbit and the lunar surface. The effects of mission time, LMAD location/orientation, and earth orbit orientation (inclination and node) on total delta V and trajectory shape are investigated.

LUNAR STEPPING STONES TO A MANNED MARS EXPLORATION SCENARIO;  
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The initial trips to Mars by humans will be the first real severing of our dependence on Earth's environment. Common sense dictates that a human departure from Earth measured in years, to explore a distant planet, requires systems, techniques, and operations which have solid credibility proven with space experience. The space test and verification experience must occur with Mars-like conditions but under proving ground philosophies such as good instrumentation, close monitoring, and fast emergency recovery capabilities. The lunar environment is the only arena which satisfies the requirements of a space planetary proving ground. The objective of this scenario is to demonstrate a program planning approach which has human exploration of Mars as the goal but, prudently, capitalizes on manned lunar project facilities, operations, and experience to enable a safe journey for the first Mars crew. Most of the Mars mission aspects can be proven in the lunar environment providing "stepping stones" to conducting the first manned mission to travel to Mars and return safely to Earth.

The stepping stones are presented in terms of mission objectives, mission requirements, plausible systems elements and transportation performance, human aspects, mission activities synthesis, and resource/programmatic considerations. Examples of stepping stones to be proven in the lunar planetary exploration environment which are necessary for the successful achievement of on-site human exploration of Mars include:

- (1) EVA-based planetary field exploration,
- (2) use of common technology for Mars mission application,
- (3) establishment of confidence in the Orbit Transfer Vehicle,
- (4) inspace storage and handling of cryogenic propellants,
- (5) establishment of operational confidence in aerobraking,
- (6) establishment of precise inspace launch capability,
- (7) development and regular use of automation systems,
- (8) development of planetary outpost site management,
- (9) operation of on-site planetary sample analysis equipment,
- (10) operations experience in planetary drilling/digging,
- (11) establishment of exploration planning methods, and
- (12) the use of lunar resources directly in the Mars program.

The approach used to develop the scenario is to identify major manned Mars mission concept alternatives and to select a set of technologies, elements, configurations, and operations which utilize and depend on the stepping stone requirements. The set of mission building blocks is selected based on designs which exclude use of controversial technology leaps, minimize the Mars-bound vehicle initial weight prior to transmars injection, use common systems, and provide schedule and configuration flexibility. A lunar/Mars program is then illustrated which applies these stepping stones to the first on-site, human exploration of Mars and an eventual long term transportation system.



ENABLING LUNAR AND SPACE MISSIONS BY LASER POWER TRANSMISSION;  
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A number of system studies have identified potential applications of and scenarios for power transmission in near-Earth space Refs. 1, 2, and 3) and at Mars (Ref. 4). In this paper, applications are proposed for laser power transmission at the Moon and near-Moon space. Although there are a number of laser power sources available, most recent interest has focused on the solar-pumped laser (Ref. 5). In this scenario, a large solar collector would collect and focus sunlight onto a transparent cell containing, for example,  $C_4F_9I$ . In this case, the molecule would photodissociate and create excited atomic iodine which, in turn, would lase at  $1.315 \mu m$ . The beam would be directed to large transmission optics, then beamed to distant users. Multimegawatts of laser power would be received by user spacecraft and converted into electricity or propulsion.

On the lunar surface, prospecting rovers would be much more flexible and lighter since they would not need to carry their primary power source. Laser power would be beamed to the rover only when needed and at power levels needed to accomplish the mission. Small human habitats could also receive power. Such habitats could be more mobile than those using stationary primary sources (e.g., SP-100). The laser beam itself could be used to probe the lunar surface producing mineral and surface contour maps. At high laser powers, laser propulsion could transport valuable cargo to lunar orbit. Lunar space power requirements could also be met with laser power transmission. This would allow more flexibility for the user (receiver) spacecraft in its lunar space location for powering its science, materials processing, or other missions.

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## THE NEED FOR ARTIFICIAL GRAVITY ON THE MOON

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There is no guarantee that lunar gravity will provide sufficient physiologic stresses to the body. In fact, it may be the case that the same physiologic deconditioning seen in zero gravity may also be seen on the surface of the moon.

Our journeys into the weightless environment of space, and the fractional gravity of the moon, have clearly demonstrated the ability of humans to work comfortably and precisely in zero and one-sixth gravity. We have also learned that extended periods in zero G can be detrimental to an astronaut's health. Experiences on Skylab, Salyut, and Spacelab indicate that durations in space on the order of days lead to space adaptation syndrome (motion sickness) and immunosuppression, while stays on the order of weeks begin the process of muscular atrophy, osteoporosis, cardiovascular deconditioning and body fluid/metabolite shifts which make the return to a terrestrial gravity environment difficult. Once the body has been allowed to adapt to the weightlessness, a "readaptation" to the stressful gravity of Earth may take weeks of bed rest.

The possibility that serious physiologic deconditioning will occur one-sixth gravity is of particular concern for those inhabiting the "lunar colonies" of the future in which people plan to spend the majority of their lives and raise families. After a critical period of time, individuals living in lunar gravity might not be able to return to the stressful one gravity of Earth. Also of concern is the question of whether human embryo development (gestation) can occur in fractional or microgravity.

The concept of rotating space habitats in Earth orbit has been proposed to provide the human pioneers of space with centripetal acceleration as a replacement for gravitational acceleration. It might also be the case that a rotating habitat on the Moon is both necessary and effective. From the medical stand point this concept is attractive because it counters the physiologic barriers to long-term fractional-gravity habitation discussed above. In addition, and perhaps as important, it also provides a living environment which is compatible with our current social, physical and psychological needs. Thus, the centripetal acceleration of a rotating habitat could be adequate for raising an infant or conducting surgery.

This paper outlines the arguments for and against artificial gravity on the moon, and reviews the unique problems which exist for humans living on a rotating habitat of finite radius (motion sickness induced by "Coriolis Cross-Coupling", Coriolis force causing deviation of body limb motion, and perceivable gravity gradients). The paper goes on to examine the physiologic limitations that these unique problems place on the parameters of habitat radius and rotation rate. Conclusions are based on research in the fields of vestibular science, human factors, brain science, and neuromuscular physiology. An effort is made to pull together scattered research from these fields to shed light on the question: "What is the maximum angular acceleration rate, and smallest radius possible for a rotating habitat providing terrestrial gravity?" The report examines long duration studies conducted in the Pensacola Slow Rotation Room, vestibular adaptation studies from Skylab and Spacelab, brain plasticity research in the visual, vestibular and muscular systems, and the perceived requirements by the cardiovascular, musculoskeletal, and immune system. The report concludes by proposing a number of additional research projects which could answer key questions for designing a lunar rotating habitat.

ISSUES FOR JOINING OF LUNAR STRUCTURAL MATERIALS;  
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It has been proposed that building materials for lunar bases could be developed in-situ using lunar soil as the raw material. The soil could be mixed as a concrete and cast [1,2], sintered into useful shapes [3], or serve as the source of ingredients from which glass fibre - reinforced composites would be formed [4]. Once structural members have been formed as bricks, beams, tubes, etc., they must then be joined together for functional applications.

The technology of joining ceramics and composites for terrestrial applications is just now emerging. Undoubtedly, new developments in these fields will be adapted for lunar operations. This paper identifies and discusses some of the key issues which will require attention in the process of developing joining methods for lunar materials. The four primary areas which must be considered are: 1. process selection, 2. equipment development, 3. quality assurance, and 4. repair techniques.

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# A LUNAR POLAR EXPEDITION

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Advanced exploration and development in harsh environments requires mastery of basic human survival skills. Expeditions into the lethal climates of Earth's Polar regions offer useful lessons for tomorrow's Lunar Pioneers.

Techniques of expedition management, base/depot logistics, team composition, and prudent use of both proven equipment and innovative procedures are applicable to survival and success on Earth or Moon.

In Arctic and Antarctic exploration, "wintering over" was a crucial skill. The ability to establish a supply base and survive months of polar cold and darkness made extensive travel and exploration possible.

This paper examines a minimal, low-cost scenario for supporting a small expeditionary team on the Lunar surface for one year.

This establishment of a long-term human presence on the Moon is a prerequisite for advanced science, exploration or industrial utilization of Earth's nearest celestial neighbor.

Transportation and life support requirements for a five-person Lunar expedition are specified, and a system design presented.

A mass budget of 35,000 KG to be delivered to the Lunar surface includes equipment and consumables.

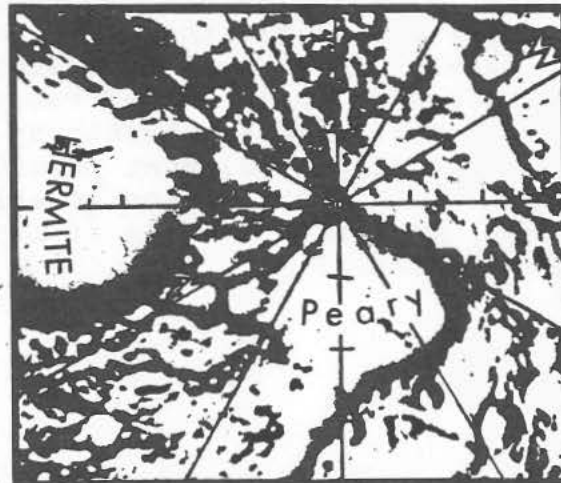
With 75% water recovery and no other recycling, life support consumables constitute 30% of the mass budget for the full five-person crew.

Cargo landers and a crew descent/return vehicle are described. A derivative of the Lunar Module Descent Engine serves as main propulsion.

Special attention is given to a 15KW power system and the unique advantages offered by locations near the Lunar poles. Existing information characterizing the north Lunar pole is reviewed.

To ensure both low development cost and safety, the proposed spacecraft configurations, mission profiles, Lunar surface facilities and life support systems rely on proven technologies.

The Lunar Polar Expedition described, conducted during the 1995-2000 "Quiet Sun" period can provide a basis for permanent occupancy, scientific exploration and industrial development.



North Pole (N) and 12 km crater on lip of Peary Crater (45 km).

## A LUNAR BASE SCENARIO EMPHASIZING EARLY SELF-SUFFICIENCY

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Previous scenarios for a lunar base have proposed early development of propellant (namely oxygen) at the lunar surface in order to reduce the transportation costs of later deliverables by offsetting earth-to-orbit propellant costs. Also, closing the life support system and providing lunar production facilities for metals and ceramics were viewed as later elements in the base development. However, such elements are critical to ultimate base self-sufficiency. In such scenarios, operational costs associated with the transportation of crew, habitation, and resupply are substantial. In addition, the economics of lunar oxygen production are inherently limited by the requirements to transport hydrogen to space, by the need to transport (or provide) aerobrakes, and by the operational costs.

The proposed concept for early self-sufficiency has the following strategy. The initial habitation consists of a minimal number of Space Station modules. The initial power supply of a 5-10 MWe nuclear system provides an energy-rich environment. Subsurface tunneling is used to rapidly expand the habitable volume, making possible the early introduction of a closed life support system and a local food supply. Volatiles for the pressurization of the expanded habitat, expansion of the biomass, and water reservoir are obtained by the processing of the lunar regolith. Finally, equipment provided for oxygen/metal pilot plants allow early production of utility system components, aerobrakes, and the expansion of productive capability utilizing indigenous material

LUNAR LAW -- REGULATION OF HUMAN ACTIVITIES ON THE NEW FRONTIER; A. M. Dula, Dula, Shields & Egbert, 6900 Texas Commerce Tower, Houston, Texas 77002

("What do you mean the U.S. says you're not a claim jumper! We'll go see Judge Dula about that!")

Human activities in space over the last thirty years have created a varied body of international and domestic space law. This law is evolving from vague and academic international treaties to definite national law and regulation controlling specific subjects. This paper addresses the current legal regime for a lunar base engaged in using natural resources on the moon for profit. It discussed the so-called "moon treaty," which is now in effect, though not signed or ratified by either the United States or the Soviet Union. The author concludes that a set of definite U.S. Federal Statutes, much less like the Northwest Territories Ordinance, is required to enable free enterprise to work effectively in the high frontier of space.



# Generating Revenues in Space: Challenging some of the Economic Assumptions of Space Exploitation

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Scientists and policy makers alike are becoming increasingly concerned as to the economic viability of the exploitation of outer space. Remedies for the high cost of doing business in space traditionally have centered around ways to lower transportation costs to Low Earth Orbit (LEO). To date, there has been insufficient analysis of the other side of the equation; exploring ways to increase revenues from space ventures.

This paper will challenge some of the economic assumptions created by previous government monopolization of space activities. NASA's mission, afterall, is to advance scientific knowledge concerning outer space, not provide low cost space transportation systems or turn a profit. Private entrepreneurs attempting to participate in space ventures, therefore, are faced with high transportation costs to get into space, and little or no opportunity to generate secondary revenues (revenues not from the sale of products manufactured or services rendered in space).

Through the example of a one-shot Mars private sector venture, a myriad of revenue generating activities can be contemplated. Analysis of the "Mars or Bust" mission reveals the following revenue generating and cost-cutting opportunities:

1. Selling the broadcast rights to the mission;
2. Capitalizing on NASA's mandate by trading information and Martian soil samples for launch services; and
3. Bartering for systems. Exchanging publicity rights for essential subsystems such as computer and life support.

The result is that rather than being totally out of the realm of possibility, a private sector Mars venture is theoretically viable. Although this author does not advocate such a short-sighted mission, the example demonstrates that private ventures need not conduct themselves just like the NASA has while in space. The same techniques, to varying degrees, can be applied to lunar developments as well.

## Conclusions

Entrepreneurs seeking to exploit the resources and environment of outer space must discover new ways to profit from their efforts. Conducting "business as usual," i.e. business as it has been conducted by government entities during the past thirty years, is inefficient. Only by abandoning old assumptions and instituting creative revenue measures will the full potential of outer space be realized.



LUNAR BASE CELSS-A BIOREGENERATIVE APPROACH; G. W. Easterwood<sup>1</sup>, J. J. Street<sup>2</sup>, J. B. Sartain<sup>2</sup>, D. H. Hubbell<sup>2</sup>, and H. A. Robitaille<sup>1</sup>. <sup>1</sup>Soil Scientist and Director, The Land, EPCOT Center, Walt Disney World Co., P.O. Box 10,000, Lake Buena Vista, FL 32830-1000, and <sup>2</sup>Associate Professor of Soil Chemistry, Professor of Soil Fertility, and Professor of Soil Microbiology, Department of Soil Science, 2169 McCarty Hall, University of Florida, Gainesville, FL 32611.

During the 21<sup>st</sup> century, human habitation of a self-sustaining lunar base may be a reality. To achieve this goal, the occupants must have food, water, and an adequate atmosphere within a controlled environment for survival. Due to the harsh environment of the moon, advanced technology must be employed to initiate processes that have existed since life began on earth.

A bioregenerative approach to lunar base CELSS may provide essential products with minimal resupply from earth. An entirely theoretical conceptual life support system, based on food production, waste management and utilization, and product synthesis is outlined. Inputs into the system include an atmosphere, water, plants, biodegradable substrates, and manufactured materials from lunar sources such as fiberglass containment vessels, and water filtration systems. Outputs include purification of air and water, food, and hydrogen generated from methane.

THE ART AND SCIENCE OF PLANNING FOR A LUNAR BASE; Alice Eichold, School of Forestry and Environmental Studies, Yale University, 205 Prospect Street, New Haven, CT 06511

Provision for air, water, food and shelter are the first order of business in any human effort to live on the moon. For any long duration mission, human habitability becomes the fifth essential design criterion. Mitigation of the psychological problems imposed by confined isolation is one of the most difficult obstacles to overcome in space exploration. It is the responsibility of the environmental designer to optimize every human factor dimension, even though such decisions are virtually impossible to quantify; as well as to optimize provision for air, water, food and shelter. Growing plants for ecological life support can provide the first three items, but plants too must be sheltered in outer space. As living things that are beautiful and interesting unto themselves, the plants must be made visible to the humans, a part of their everyday experience. Some philosophical consideration of the relationship between humans and their environments is crucial to the successful design of space habitats. This study examines some of the classic literature of environmental planning, anthropology and sociology with an equal emphasis on science and art. The general principles derived from these readings accommodate doubt, contingency and ambiguity as givens in the environmental design world.

EXTRATERRESTRIAL APPLICATIONS OF  
SOLAR OPTICS FOR INTERIOR ILLUMINATION

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Research into the development of beamed sunlighting systems for terrestrial applications has been intermittently pursued since the turn of the century. A sustained effort began in 1978 when BRW started developing solar optic technologies for concentrating beamed sunlight into remote interiors of Earth-sheltered buildings. The impetus for this research and development, the need for energy conservation, as well as the applied criteria, lightweight and low cost materials which minimize volumetric requirements, parallel those of NASA's CELSS program and Lunar base applications. The scope of the detailed research and development of a particular solar optic technology, prism light guides, includes identifying the efficiency of the distribution system, establishing photometric characteristics, identifying integration issues with other building systems and an economic life-cycle cost analysis. This research has been funded by BRW, the State of Minnesota, the Department of Energy and Battelle Pacific Northwest Laboratories.

BRW pioneered Earth-sheltered construction for commercial buildings, thus becoming experienced with the technical issues of construction and conservation. Social and psychological issues of the users of limited access environments were also addressed. Chief among the users' concerns were color, texture, view opportunities and natural illumination. BRW was commissioned by the State of Minnesota to design a laboratory facility as "an Earth-sheltered energy independent demonstration project." Two solar illumination systems were created and implemented for this project: a Passive Solar Optic System (PSO) for general illumination and an Active Solar Optic System (ASO) for task illumination. Both systems make use of aluminized plastics and very thin fresnel lenses.

PSO is essentially an aperture reduction device which enables the selective tuning of an aperture for the directionality and quantity of desired sunlight. PSO systems, which rely on paired arrays of lightweight reflective fresnel lenses, are now common practice. Several aspects of ASO systems have been reduced to common practice. Among those are networks and fixtures capable of delivering beamed sunlight and/or electric light, selective coatings, control systems and heliostats. The unique aspect of our work in this field has come from the use of prism light guides for the transportation and distribution of both sunlight and electric light. The light guides are hollow tubes capable of many sizes and shapes that transfer light using the principle of total internal reflection. The use of hollow light guides reduces the weight of terrestrial systems by a factor of 2000 when compared to fiber optic systems. A complete system is presently operational.

Consideration should be given to beamed sunlight alternatives for growing plants and illuminating human habitats because of the ability to transmit selected wavelengths of sunlight and/or artificial light, the lightweight aspects of the system, current developments in photovoltaic powered, random targeting heliostats, and the high operations and maintenance costs of all-electric systems.

THE ROLE OF COMPUTERIZED MODELING AND SIMULATION  
IN THE DEVELOPMENT OF LIFE SUPPORT SYSTEM TECHNOLOGIES

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and

Michael Modell, Modell Development Corporation, Framingham, Massachusetts

Physical/chemical systems are expected to play a major role in reducing the resources required for long duration manned missions. Life support systems (LSS) may be a pacing technology because many subsystems to accomplish material recycle have not been developed. There is an urgent need to develop, perfect and demonstrate new LSS technology for Space Station and beyond. The past development of LSS technology has been a slow and costly process. Using conventional means of process development, it would take decades and hundreds of millions of dollars to develop technology for recycling of water and solid waste for lunar missions within the next thirty years. Since we anticipate neither that amount of time nor level of funding, new methodologies for developing LSS technologies are essential.

The challenge is to devise new processes as quickly and as cheaply as possible. The tools available to the process developer are theory, empiricism, and reasoning by analogy. Experimentation is used to characterize those phenomena which are not adequately defined by theory or which cannot be estimated accurately by using analogies. Today, where algorithms are available for computer calculations of many phenomena, there is no question that computation should supercede experimentation wherever possible.

There are three levels of experimentation: laboratory scale, preprototypes and integrated testbeds. Preprototypes are usually very costly to design, build and test. Prior to entering this phase, the entire process should be evaluated as rigorously and as stringently as possible. Whereas 15 years ago, the lack of available theory and computational capacity may have dictated more costly experimentation, it is possible today to prove technical feasibility and appropriateness of candidate processes to LSS requirements prior to building preprototypes and conducting costly experimental programs.

Computerized modeling and simulation (CMAS) is a tool that can greatly reduce both the time and cost of technology development. By CMAS, we refer to computer methods for solving the phenomenological equations of physical/chemical processes (i.e., process conditions based on properties of materials and mass and energy balances, equipment sizing based on rate processes and the governing equations for unit operations). Over the past ten years, several such computerized packages have become sophisticated enough to be used to design and simulate highly complex and integrated chemical and petrochemical processes and facilities. In particular, CMAS systems can be used to evaluate a LSS process design with minimal requirements for laboratory experimentation. Several applications of CMAS to LSS technologies are discussed.

## EARTH-BASED ANALOGS OF LUNAR AND PLANETARY FACILITIES

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Larry Bell - SICSA\*

Guillermo Trotti - SICSA\*

A precursor step to the establishment of permanent lunar or Mars bases will be the development and testing of the required technologies and hardware. Increasing attention is being given to the creation of an Earth-based research and test facility that would simulate as closely as possible the construction and continuous operation of such a base.

This activity might develop as a project of a public/private consortium of government, industry, and academia on a national - or perhaps international level. These partners would share expertise, risk, and near-term benefits and help guarantee the long-term sustained commitment that will be required.

Specific goals of this project would be:

To develop and test by terrestrial analog, those systems that will be required at a permanent planetary base;

To investigate life science issues including studies of human adaptation during long isolated periods in severe environments, as well as animal and plant growth experiments;

To create a national and international focus for space technologies development that have potential for near term commercial benefit;

To define pathways for private industry to extrapolate their terrestrial expertise into future space activities;

To bring together an international community that might be instrumental in helping structure long-term space policy.

The precise fidelity of the simulation would be determined by a tradeoff between expense and need. It's envisioned that astronauts would live in tightly controlled habitats in a hostile environment for an extended duration.

Research would be pursued in Earth and planetary sciences, life sciences, technology demonstrations including life support, power, resource mining and processing, and human operations testing, including construction, base operations, and psychological factors.

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## POWER SYSTEM CONCEPTS FOR LUNAR SURFACE MOBILE EQUIPMENT

by

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Marla Perez-Davis \*

Surface mobility will be required once man establishes a presence on the lunar surface. Various functions will be required to support the operations of the "Lunar Base" and many of these will require mobility to either move equipment, cargo, personnel, or to carry out surface exploration of the lunar surface. This paper discusses the power and energy requirements for such mobile equipment.

A number of candidates have been investigated for the power and energy systems of the equipment to carry out these various operations. A matrix showing the various functional power/energy and operational requirements has been constructed, (FIGURE I). Power/energy system concepts have been developed for the mobile equipment which will carry out these functions and are presented in the following paper.

A Hydrogen-Oxygen fuel cell system has emerged as the prime power system candidate for this type of mobile equipment. Shuttle derivative fuel cell technology, (FIGURE II), with modest projections for the state of near future technology advances, will satisfy the requirements for the initial phases of these colonies and bases. More optimistic projections for the technologies are made for advanced bases of the intermediate future. For the extremely long range future, fuel cell systems just now in the research stage will support the "mature" bases of that time frame.

This paper also discusses the systems studies and trade offs which lead to the selection of the power system for the concepts shown in the matrix. Projections of the technology advances for the intermediate and the long term future are examined in detail and their effect upon any particular application is analyzed in detail. Further, many of the power system applications to support the lunar activities could be used to support activities on other planets as man extends his horizons to the remainder of the universe. The Hydrogen-Oxygen fuel cell again emerges as the prime power system candidate for applications other than Lunar surface mobile equipment.

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## LUNAR SURFACE MOBILE EQUIPMENT

Candidates For  $H_2-O_2$  Fuel Cell Motive Power System

Attributes	Power (KW)		Energy (KWHRS)		Range (Km)		Duration (Days)		No. of Occupant	
	10	100	1000	500	1000	10	100	1	10	100
Applications										
Surface Exploration Veh.	•			•		•		•		•
Personnel Transp. Veh.										
Intra Base	•		•		•			•		•
Inter Base		•		•		•			•	
Cargo Vehicles										
Light Utility Truck	•		•		•			•		•
Heavy Truck		•		•		•			•	
Excavator/Digger		•		•		•		•		•
Bulldozer/Grader		•		•		•		•		•
Mobile Cranes										
Heavy Lift	•	•	•	•	•	•	•	•	•	•
Light Lift										

Figure I

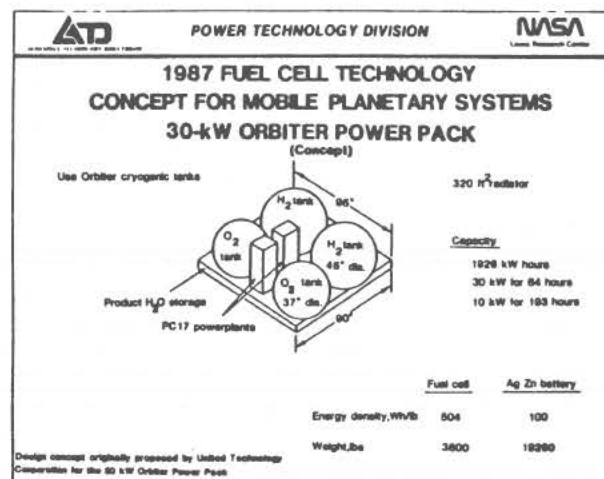


Figure II



## BIOLOGICAL LIFE SUPPORT SIMULATION FOR A LUNAR BASE

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A biological life support system (BLSS) for space application has been modeled and simulated with ENHANCED DESIRE (Direct Executing Simulation In Real Time). ENHANCED DESIRE was originally conceived as a dynamic system simulation package to solve a large number of linear or non-linear ordinary differential equations. The program is unique in that the mathematical representations and input parameters can be typed on the terminal screen and then simply solved by typing a RUN command which produces an immediate graphic response. This type of equation solver is very user friendly and provides immediate response for the programmer during model design and then during application studies.

The model described is for a biological life support system as would be envisioned at a lunar base or campsite. The objectives are to investigate the time-dependent variations of key performance parameters such as material and energy flow over periods ranging from days to years. One component of the model determines the light levels from solar or artificial devices. A crop model simulates the growth of vegetable crops needed to produce food and oxygen based on light and nutrients. The growth model is driven by leaf photosynthesis and plant respiration. The overall ecosystem model yields mass and energy transfer rates from the various components in the enclosure, including humans, animals and microbes. The interactions include gaseous exchanges--primarily carbon, oxygen and  $\text{CO}_2$ . In addition, the plant matter is broken down as food for human and animal consumption. Ultimately the waste products generated by the occupants and the plant refuse must be further broken down and returned into the system with the aid of microbial activity.

A case study demonstrates the use of the model; it involves ten human occupants and is used to develop some baseline design parameters for a self-regulating regenerative BLSS on the moon.

CONSIDERATIONS FOR FIRST GENERATION LUNAR  
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The difficult economics of supplying a manned lunar base with food from earth will force the early establishment of a lunar agricultural system. This system will be designed for the reliable production of basic food crops and the recycling of air and water.

It is likely that the first food production units will be aeroponic or hydroponic units since these units can be brought into production with a minimum amount of mineral imports from earth. These units could be counted on to produce a variety of vegetables and grains for the crew of the lunar base.

Hydroponics or aeroponic agriculture tends to be complex and unforgiving, needing constant monitoring. Individual modules must be isolated from each other to prevent catastrophic infestation of algae and/or pathogens. Each module must also be periodically taken out of production and cleaned. Use of hydroponics or aeroponics will also reduce the choice of crops which may be grown at the lunar base. A wide range of crops would be desirable for psychological reasons and food supply reliability. If some crops do not perform well in the lunar base environment, a wide range of crop types would guarantee a sufficient volume of production.

For these reasons, at least some of the agricultural production should use amended lunar soil. This soil-based agriculture offers the major advantage of a highly reliable, forgiving agriculture that utilizes local resources. The soil-based agriculture has the major disadvantage of requiring a larger stock of initial resource imports from the earth.

The growing areas will require a relatively intense level of lighting delivered in an optimal day and night cycle. Use of any form of currently known illumination will generate a large amount of heat along with the light. Active refrigeration means, such as peltier effect solid state refrigeration, will be required to remove excess heat from the areas for use elsewhere in the lunar base environment.

**POWER REQUIREMENTS FOR LUNAR BASE SCENARIOS**

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The initial elements of an ambitious program strategy for human exploration beyond Earth have been developed and presented to the highest levels of NASA management for their consideration in planning the future goals and direction of the Agency. The Lunar Base Initiative is one such advocacy plan. A major space goal of this magnitude can only be implemented by a series of program phases evolving from precursor robotic missions, to early piloted flights for investigation of potential outpost sites, including the initial development of temporary surface stations and buildup of operational experience, through the eventual establishment of permanent and sustained surface bases. Each phase in this scenario will require distinctly different levels and types of power sources to support both transportation and on-surface operations.

This paper will identify and describe the respective types and specific amounts of power required by all major system elements in a phased program of lunar exploration over the time period 1990-2030. System elements include orbital test and staging facilities, various types of transportation vehicles, and emplaced surface facilities related to science experiments, life support, exploration, and resource utilization. Phase 1 of this program employs a variety of robotic lunar orbiters, rovers, and possibly sample return to obtain a comprehensive database on topological mapping, geochemical assessments, seismic activity, and gravity maps. Power requirements during Phase 2, beginning with piloted flights around the year 2000, increase by at least an order of magnitude (50-100 kWe) with the emplacement of habitat modules, closed-loop life support, personnel transporters, construction equipment, optical and radio telescopes as well as other limited science facilities, and R&D pilot plants for lunar oxygen production. An additional factor of three to ten power increase may be expected for the permanently occupied base of Phase 3 which adds major science facilities, operational LOX production, and significant R&D facilities in life science, CELSS, and ceramics processing. The power demands of the self-sustained operational base in Phase 4 can easily reach several megawatts.

A wide variety of power system technologies applied across the exploration scenarios are examined; these include photovoltaic (with battery or fuel cell energy storage), solar-dynamic, RTG's, and nuclear reactors. A comparative assessment of technology trade-offs and design problems is made to ascertain the most appropriate application for the different phases as well as to identify synergistic development across the program. The discriminators used for this assessment include power system mass and size, total mass in LEO, technology readiness, operational impacts, safety concerns, and other factors.

## THE MANKIND PROVISIONS RECONSIDERED: A NEW BEGINNING

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The Common Heritage of Mankind and the Province of All Mankind are different legal ideas developed in international space law during the last quarter of a century. The term, "province of all mankind" appears in the 1967 Outer Space Treaty which established the primary basis for the legal order of space. The term "common heritage of all mankind" is contained in the Moon Treaty and the Law of the Sea Convention.

Since the initial appearance of the mankind provisions in international law, controversy has arisen regarding their intent and meaning as applied to a nation's right to explore and use common environments and its nation obligation regarding benefits derived from those environments. Different interpretations are currently competing for acceptance. This is so, in part, because although, in the case of the Outer Space Treaty, general principles were articulated, rules for acceptance and application of the principles were not. In the case of the Moon and Sea Treaties, despite efforts to clarify both meaning and application, the articulations are still too vague for legal certainty.

Rather than detail the legal merits and liabilities of all competing interpretations of PAM and CHM, this paper will focus on the fact that these concepts are already currently available tools for the advancement of both global and United States interests but, because of the labyrinthine legal arguments that have been generated and some assumptions being held, they are in danger of being lost as such tools. The tendency of many U.S. observers to interchange PAM and CHM and assume that both are incompatible with U.S. interests, particularly in space, will also be addressed. It is suggested that, particularly in light of recent developments in legal thinking and political conditions, PAM and CHM can yield positions compatible with U. S. interests and that it can and should seek their use, both in law and the political arena, as a basis for global cooperation and benefit.

Despite the uncharacteristically high degree of U.S.-U.S.S.R. agreement that accompanied the inception of the Outer Space Treaty and its overwhelming international acceptance, in the decades since its appearance in international law, factions within some nations have sought to eviscerate the progressive, peaceful and painstakingly developed concepts it contains. Both the spirit and meaning of the Treaty have been attacked by interpretations advanced by lawyers, politicians and business-people of various nations that are, ultimately, bottomed on the erroneous belief that the infinity of space and its resources cannot provide for all of Earth's people in peaceful co-existence. At its very core, there can be no other reason for the sophisticated and complicated maneuvering occurring among the nations. The time has come to reconsider where this lethal course of action, driven by fear, is leading.



## GENESIS AND APPLICATIONS OF A POLAR LUNAR POWER RING

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A ring-like grid of modular photovoltaic solar collector assemblies linked by power transmission cable, and encircling a Lunar pole at a latitude of 80 to 85 degrees, is proposed as a primary research, development and construction goal for a lunar base in a polar latitude and for lunar development in general. The Polar Lunar Power Ring results from a perceptual and mathematical search for a safe, simple, reliable, and inherently expandable continuous power source capable of acting as the foundation for a large diversity of Lunar development ranging from agricultural life support systems to plasma based refinement and fabrication techniques (seamless CELSS). The moon is a slowly rotating body under 1400 watt/meter square solar irradiation. In order to: conserve nuclear fuel for solar independent missions, reduce dependence on energy storage technology, and reduce the length of a equatorial power grid (11,000 km), a circular power grid of 2,000 km based on solar collectors (10x10 meters) affixed to each transmission cable pole or tower is conceived. Except for GaAs converters the required material would be produced from lunar materials. An assembly goal of 1 km per day both ways at 100 meter tower spacing adds 0.28 megawatts/day for a ring closure goal of 90 megawatts continuous excluding losses. An initial base would be established to fabricate and construct using a dual tracked railway, minimizing Lunar dust problems and allowing larger equipment and fast access. The railway would allow human habitations to follow the construction front and expand the ring as lunar development ensued. Operation and maintenance of the ring should be man tended, non military and off bounds to AI. Teleoperation and telerobotics can be used to assemble a resource base and initial equipment to prepare for assembly of the main construction base. Humans would arrive and proceed, assisted by teleoperation and science and engineering teams on Earth. External southwalls of craters Plaskett, Nansen and De Sitter could be sheathed with minimal effort. High energy consumption processes can be considered allowing construction of spacious facilities and high quality seamless CELSS, to assure safety for permanent lunar habitation. High energy research can begin, sparing nuclear and chemical fuels for more adventurous journeys to farther reaches, and towards a fleet to address the shortage of volatiles. It is emphasized this energy system must not be used to power directed energy weapons or otherwise in conflict with Earth, the home of life, for this reason, designs and operations must preclude any possible chance of commandeering the output, by humans or rogue AI. This is to be given serious thought due to the hardened position at subsurface farside Lunar facilities. In conclusion, the polar power ring can determine initial lunar base placement, ensure energy for permanent habitation, and generate another generation of space technology from a solid research and test bed. On completion, lunar development proposals can be assured of rapid access to continuous solar derived electrical energy and clean efficient rail transport as the power infrastructure is expanded. Also, 2 poles means competition and sharing, an opportunity for co-operative good will.

## **ADAPTION OF SPACE STATION TECHNOLOGY FOR LUNAR OPERATIONS**

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A number of the Space Station system technologies have significant potential for direct utilization in lunar operations. Specifically, data management, EVA, power, module structures, work stations, and propulsion are all station systems which have equipment that could be easily and directly incorporated into an early lunar lander, space station, and/or surface base. Several other technologies, such as thermal control, guidance and navigation, life support, and communications may also provide spin-off opportunities, but to a lesser degree.

In addition to capitalizing on the technical advantages of off-the-shelf equipment (i.e. - reduced development, design, test and evaluation; improved reliability), the use of Space Station hardware also generates several programmatic benefits. First, the production of the lunar mission hardware would optimally be scheduled to occur as that of station items wind down, thereby making use of existing manufacturing facilities. The procurement of standard data processors, multiplexers, power switching devices, etc., for a lunar base could be done together with Space Station spares and replacements. Secondly, a common spares pool would be smaller and less expensive than separate ones for the Station and lunar programs.

In summary, the use of Space Station technology for lunar missions will a) shorten schedules, b) reduce costs (especially those up-front), and c) lower both operational and programatic risks.

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Various NASA/McDonnell Douglas Space Station documents



**Table 1: Potentially Common Hardware Items**

"X" indicates commonality

<u>Equipment</u>	<u>Lunar Base</u>	<u>Orbiting Lunar Station</u>	<u>Lander</u>
Data Management System			
- Standard data processor	X	X	X
- Multiplexers	X	X	X
- Fiber optic data bus	X	X	X
- Mass memory unit	X	X	
Module Structure			
- External hulls	X	X	X
- Work station panels	X	X	X
- interface connections	X	X	X
- Docking and berthing fixtures	X	X	X
Communications and Tracking			
- Local radio receivers and transmitters	X	X	X
- Internal video and audio	X	X	X
Guidance, Navigation & Control			
- Star trackers		X	X
- Inertial sensor assemblies		X	X
- Control momentum gyros			X
Thermal Control			
- Module H <sub>2</sub> O cooling loop	X	X	X
- 2-phase ammonia heat lines	X	X	
- Radiators	X	X	
Propulsion			
- GH/GO thrusters		X	X
- GH/GO storage tanks		X	X
Power			
- Transmission cable	X	X	
- Switching devices	X	X	
- DC-DC converters	X	X	
- Power generators	X	X	
EVA			
- Airlock	X	X	
- Hyperbaric chamber	X	X	
- Suit	X	X	

A STATISTICAL ANALYSIS OF A LUNAR BASE AS AN IMPORTANT STRATEGIC  
OPTION FOR NASA

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In an effort to quantify the significance of a Lunar Base initiative for the civilian U.S. Space Program (NASA), a statistical clustering analysis of a large number of major space projects, both planned and realized, has been undertaken. This analysis was stimulated by internal NASA studies concerning Space Leadership and Strategic Option Development. In a recent study led by Dr. Sally Ride, four major space initiatives were outlined as programs capable of reasserting U.S. Space Leadership in key areas [Ride, 1987]. One of the initiatives discussed in the report is a permanent human-occupied Lunar Base; in contrast, other initiatives range from human exploration of Mars to intensive robotic exploration of the planets or of the global Earth system. While there is no question that any or all of these multibillion dollar efforts are leadership programs in the world space arena, recent work undertaken by a special task force (1A) working under Dr. Ride and others have noted that no single major initiative constitutes a viable strategic plan for NASA. In other words, the continuity behind the vision and objectives for the 4 initiatives under consideration is not clear, and strategic perspective has not been applied to their definition. For example, a strategic look at the Lunar Base option would ask: "What kind of base do we need or want to realize our goals in areas such as exploration, science, technology, and operational capabilities?". A similar question can be asked of any of the major initiatives. Thus, if strategic emphasis is to be placed on science/exploration, then a Lunar Science Outpost (LSO) would constitute a key program in NASA's strategy, and such an outpost would not place much emphasis on operational capabilities or materials processing in order to maximize science experiments (e.g. early Antarctic science research outposts). Of course, the evolution of an initial LSO might lead to more general capabilities if the strategic objectives so dictated. Other varieties of lunar bases could be defined to fit within a clear strategic framework with emphasis on areas such as materials processing, closed life support, spaceport, energy production etc. Again, similar arguments could be applied to other planned leadership programs, including space stations, human Mars missions etc. With such issues in mind, the approach taken in this semi-quantitative study has been to try to discover where a general-purpose Lunar Base might fit within the larger set of previous and planned space activities. By developing a set of boolean attributes derived from various filters (e.g. environmental, cultural, space policy, budget etc.), and applying them to a large set of space programs including a Lunar Base, a boolean database suitable for divisive clustering analysis was generated. A heirarchical, divisive clustering technique which makes use of an information theoretic similarity function (and implemented in APL) was applied to the data, with the result that a general Lunar Base program falls within the cluster of programs/activities which have largely constituted the great successes of NASA's past 25 years (including Viking, Voyager, Mercury, etc.). Further boolean criteria are under development to explore relationships between a Lunar Base and other major programs.

**LUNAR OBSERVER LASER ALTIMETER FOR LUNAR BASE SITE SELECTION**

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One of the most basic parameters for describing the surface configuration of any planet is topography, and an accurate knowledge of this parameter at a variety of spatial scales is essential in planning surface activities, whether by humans or robotic systems such as rovers. The aim of this report is to present a case for obtaining extremely high vertical and horizontal resolution topographic data for the Moon by means of a laser altimeter instrument on a future lunar polar orbiter such as the proposed Lunar Observer. Our basic assumption is that a knowledge of local relief at scales commensurate with human or rover activities (i.e., meters to 10's of meters) is critical to effective selection of potential Lunar Base sites, and further that quantitative relief data of this type will be invaluable in geomorphic studies of lunar landforms and processes, perhaps as a supplement to existing and future imaging datasets.

The topography of the near-side of the Moon is well-known at spatial scales of 100's of meters on the basis of stereophotogrammetry from metric camera images and radar altimetry (both Earth-based and orbital). On the basis of synoptic imaging of most of the lunar surface, the morphology and relative relief of the major surface types and landforms is presently available, although quantitative relief data exists only for limited equatorial regions in the form of LTO maps. The proposed Lunar Observer mission offers the next opportunity for obtaining global topographic data for the Moon, and represents a critical precursory step before Lunar Base design and site selection can seriously commence. A polar-orbiting Lunar Observer could readily make use of existing radar altimetry techniques (e.g. Mars Observer or Magellan radar altimeter instruments) to map the global topography of the Moon at a spatial resolution of a few km and with a vertical precision of several meters to tens of meters. A global elevation model of the Moon at such spatial scales (e.g., a 2 km grid) would be invaluable for geophysical studies of crustal density structure, but would not provide data of critical importance for Lunar Base site selection (or rover trafficability; 10-100 m scales), nor could it address fundamental problems associated with lunar geomorphology (e.g., volcanism, tectonism, cratering, erosion). We have designed and simulated the performance of a simple orbital laser altimeter instrument which could profile the lunar surface with 10-50 m contiguous footprints at 30 cm vertical precision. The Lunar Observer Laser Altimeter (LOLA) would obtain circumlunar topographic profiles, as well as data suitable for computing surface roughness and near IR reflectance for small footprints. On the basis of orbital simulations, LOLA data could be used to construct a global lunar elevation grid with a 2-3 km cell size; each cell would contain over 500,000 relief measurements in spite of gaps between profiles as large as ~2 km at the equator. Our simulations have shown that virtually all lunar landform types could be quantitatively characterized, including subtle mare ridges and secondary craters often no wider than 80 m. The chronic problems with laser lifetime which plagued the Apollo Laser Altimeters are no longer an issue as a result of technology advances in all solid-state diode-pumped Nd:YAG laser techniques which can now provide billions of laser pulses (enough for a full year of operations in lunar orbit). Such lasers have the requisite narrow pulsewidths and low power requirements for use in space. As a result of our design and simulation study, we are confident that a LOLA instrument can be constructed that meets the severe weight, power, and data rate limitations imposed by the Observer-class missions. Our research suggests that local relief data obtained with a LOLA-class instrument will not only be of value in geomorphic studies of the Moon, but will be critical in Lunar Base site selection activities, as well as in autonomous rover exploration activities. (We gratefully acknowledge the support of NASA PIDDP grant 157-30-80-20, and the encouragement of L. Evans, W. Quaide, and P. Spudis; special thanks also to L. L. Aist of U. MD).

## A MANNED EXOBIOLOGY LABORATORY BASED ON THE MOON

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**INTRODUCTION:** Establishment of an exobiology laboratory on the Moon would provide a unique opportunity for exploration of extraterrestrial materials on a long term, on-going basis, for elucidation of exobiological processes and chemical evolution. A wealth of materials would be available for study by the laboratory. Immediately at hand would be a wide variety of lunar sample types and amounts as well as meteoritic material, thus there would be no restriction of sample availability at the part per billion level.

**EXPERIMENTAL:** Studies of a wide range of sample types would initially focus on the presence of amino acids, purine and pyrimidine bases, nucleosides, and other organic classes such as carboxylic acids and aliphatic hydrocarbons. Isotope studies would include D/H and the isotopes of carbon, nitrogen and oxygen.

**INSTRUMENTATION:** Although analytical techniques will advance considerably by the date of deployment, the major techniques of chromatographies and interfaced with mass spectrometry will be used to separate, identify, and measure the molecules and isotopes of exobiological interest. Miniaturization of these and other analytical instrumentations would provide scientific investigators in the lunar exobiology laboratory with the necessary research tools for identification and structural characterization of organic molecule classes in a wide array of extraterrestrial samples.

**BACKGROUND:** Our studies of the returned lunar samples (1-4) and those of others (5, 6) have shown the importance of acquiring pristine samples which have not been exposed to terrestrial contamination. Indeed, the question of contamination is continually an important aspect of studies of meteorites or the returned lunar samples, especially with regard to investigations of organic compounds. The establishment of a manned lunar exobiology laboratory, equipped with appropriate instrumentation and complement of scientists would present a unique scientific opportunity for study of extraterrestrial samples from various sources.

This presentation will discuss approaches to the analysis of the major classes of sample types, sources and organic molecules under consideration.

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LUNAR HYDROGEN: A RESOURCE FOR FUTURE USE AT LUNAR BASES AND SPACE ACTIVITIES. Everett K. Gibson, Jr., SN4, NASA Johnson Space Center, Houston, TX, Roberta Bustin, Dept. of Chemistry, Arkansas College, Batesville, AR, and D.S. McKay, SN4, NASA-JSC, Houston, TX.

With a commitment to the Space Station and the increasing interest in a potential Lunar Base, there is a need to find an extraterrestrial source of hydrogen for consumables and propellants which might be available at a reduced cost. In order to know if usable quantities of hydrogen are present in the near-earth region of space (i.e. on the moon) a study of hydrogen abundances and distributions in lunar materials has been undertaken. An understanding of the potential sources of hydrogen on the lunar surface must be obtained. If such sources of hydrogen can be identified, future space activities will be enhanced by having another source of consumables and propellants available for use. The extreme costs of transporting hydrogen from earth would be reduced if sufficient quantities of hydrogen were available in the near-earth region of space.

Hydrogen is the most abundant element in the cosmos. The sun is constantly burning hydrogen and hydrogen is being lost from the sun. In addition, hydrogen is streaming away from the sun in the form of the solar wind. Hydrogen is the most abundant element in the solar wind. It is known that the lunar surface has been irradiated by the solar wind. From the detailed studies of lunar materials, it has been shown that selected volatile elements present in the solar wind (i.e. H, He, C, N, Ne, Ar, etc.) are enriched on the surfaces of exposed materials. The longer the surfaces of the samples are exposed to the solar wind the greater the amounts of solar wind species trapped in the lunar materials.

We have been studying hydrogen abundances and distributions in lunar soils, cores, breccias and rocks in order to provide baseline information for engineering models undergoing study at the present time. From our studies it appears that there is sufficient hydrogen present in selected lunar materials which could be recovered to support future space activities. It is well known that hydrogen can be extracted from lunar soils by heating between 400 and 800° C. Recovery of hydrogen from regolith materials would involve heating with solar mirrors and collecting the released hydrogen. In order to have an understanding of the magnitude or size of the hydrogen recovery process required to recover sufficient hydrogen for space operations, we are reminded that the Space Shuttle requires around 102,000 kg hydrogen for liftoff from its launch pad on earth. Extraction of hydrogen from a mature lunar soil typical of some of those present at the Apollo 11 or 17 sites would require processing a quantity of soil equal to that found from an area the size of 28 football fields mined to a depth of 10 feet. In comparison to mining operations found on the earth, such mining operations are considered quite small.



LUNAR OXYGEN PRODUCTION FROM ILMENITE

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Pioneering space transportation and lunar resource studies have shown large payload incentives for production of lunar oxygen and have identified lunar ilmenite as a potential feedstock. Ilmenite ( $\text{FeTiO}_3$ ) occurs at abundances up to about 10 volume percent in surface-minable lunar soil; the other soil components are mainly Ca, Al and Mg silicates. One third of the ilmenite oxygen can be extracted by hydrogen at about  $1000^\circ\text{C}$  to form water, metallic iron and  $\text{TiO}_2$ . In the silicate soil components, the oxygen is much more tightly bound, so that hydrogen reduction would require much higher temperatures. Ilmenite must, therefore, be separated from these inert components by a beneficiation step also designed to work under lunar conditions. We have combined small-scale, ground-based experimental work with engineering calculations to make a preliminary, innovative design of a 1000 tonne/year lunar oxygen plant. The process is based on recycled-hydrogen-reduction of a beneficiated ilmenite concentrate feed using a continuous, fluidized-bed reactor. This work was supported by Phase I and Phase II NASA SBIR contracts monitored by Dr. David McKay at JSC.

The overall plant divides naturally into surface mining, beneficiation, ilmenite reduction/ $\text{H}_2\text{O}$  electrolysis and oxygen liquefaction and storage sections. Most of our experimental work has focused on the ilmenite reduction reactor design, and it is, consequently, the best defined equipment item. Launched weight and operating power requirements for the whole plant are about 400 tonnes and 5 megawatts, respectively. Of this total launched weight, about 45% is an allowance for the electric power source. Our work identifies the mining and beneficiation equipment design and the reactor refractory liner as two key areas where large launched weight savings may result from further research, optimized design and/or use of lunar material for construction.

Hydrogen/ilmenite reaction kinetics have been studied over the ranges  $700\text{--}1200^\circ\text{C}$  and 1-10 atm total pressure using terrestrial ilmenite samples and a fixed-bed flow reactor apparatus. This data and its interpretation will be presented and discussed. The preferred full-scale reactor, for reasons of operability and efficiency, is, however, a fluidized rather than fixed bed vessel, and its design is strongly affected by reduced lunar gravity. To begin quantifying these reduced gravity effects, physical measurements were made in transparent Plexiglas vessels using a wide range of test solids and videotaping/image digitizing techniques. Scaling correlations were developed to permit key, measured fluidized bed parameters such as bubble diameters and downcomer throughputs to be extrapolated from earth to lunar gravity. These correlations should also have value for other reduced-gravity materials processing applications.

## LASER PROPULSION FOR EARTH-MOON TRANSPORTATION SYSTEMS

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Laser propulsion is a strong candidate for use in transportation systems that will move materials between low earth orbit (LEO) and the lunar surface. Because of the very high specific impulses that can be achieved using laser propulsion, enormous potential increases in delivered payload mass are possible. This paper summarizes the different types of laser propulsion techniques that are available for use, and discusses the different earth-moon missions for which they could be used.

There is also a more complete analysis of one of the missions that appears to have the highest near-term payoff: using laser propulsion to provide the initial impulse for trans-lunar injection at LEO of an earth-moon shuttle transporting lunar oxygen. A comparison is made between a baseline chemical propulsion system and a laser propulsion system for this mission, and a study of the orbital strategies and thruster design is also presented.

It is found that laser propulsion is very well suited to the TLI-burn mission, and that the mass payback ratio of the total transportation system (defined as the ratio of lunar material brought back to LEO divided by the mass of hydrogen needed to fuel the system) can be substantially increased by using laser propulsion for this maneuver. For the sample cases considered, the MPR values increased by more than 50% over the baseline case, and maximum values near 3.0 appear possible. The MPR's were especially high when additional mass needed to be transported to the moon to aid in base construction and resupply, a situation likely to exist during the early years of base operations.

The mass of the orbital transfer vehicle tends to be limited by the available laser power, since the thrust of the laser propulsion system is directly proportional to power. However, it is shown that multiple burns in LEO can be used to greatly increase OTV masses without serious delays in trip time. A three-burn strategy results in a 253% increase in OTV mass with only a two-day delay. Problems of beam transfer between a ground-based laser, an orbiting relay mirror, and the OTV are also discussed.

A workable design for the laser propulsion thruster is described. The technical problems associated with such a thruster appear to be manageable, though some advances in window technology are needed. The mass of the thruster is very small compared to the rest of the vehicle (about 260 kg, or about 5% of the dry OTV mass). The collection optics on the OTV permit operation at ranges up to 8000 km, and can compensate for changes in beam diameter as the range increases.

## PREDICTION OF PHYSICAL WORKLOAD ON A LUNAR BASE

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The assignment of crew members to tasks that must be accomplished on a Lunar base must take into account the difficulty of those tasks. While Earth-based simulation of each task would be extremely cumbersome, an accurate method for estimating task workload may be provided by applying a prediction model developed for Earth-based jobs (1). This well-validated model utilizes an elemental analysis of job characteristics, such as the number of lifts, lowers, and distance walked. By lowering body and load weights by 5/6, an approximation of Lunar-based human energy expenditure is achieved for a given task. Because the job itself need not physically exist, many alternative job designs may be compared in their physical workload. The feasibility of using this model for low-gravity work prediction was investigated by comparing model predictions with several studies, including (1) simulated Lunar-gravity walking, (2) Apollo 14 Lunar EVA walking energy expenditures, (3) simulated Lunar-gravity bolt torquing, and (4) simulated Lunar-gravity cart pulling.

Despite its inability to account for differences in traction due to differing normal forces, the model predicted actual and simulated expenditures reasonably well. Both walking and cart pulling on level or downhill grades were overpredicted by 15-30% (using Kilocalories/minute as the comparison parameter). More demanding tasks, such as steep uphill walking or cart pulling (i.e., 15° slopes), were underpredicted by 30-50% in energy expenditure. Despite these prediction errors, the obtained values were sufficiently close to provide an objective determination of whether the job is overly fatiguing for an average crew member.

This physical workload prediction model was also applied to a conceptualized core sampling job on a Martian base (2), to determine if additional rest is required to avoid overtaxing the worker. The job, as presented, was well within physical capabilities of the worker, with no additional rest time required. The most valuable aspect of this analysis, however, was in its ability to pinpoint the most physically exhausting elements of a job. These, logically, are the candidates for redesign.

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LUNAR SETTLEMENT: PHILOSOPHY, POLITICS AND LAW

Nathan C. Goldman\*

This paper will analyze the political and legal conditions that are likely to surround humanity's return to the moon. Recounting, first the multinational focus on space and, second, the likelihood that a return to the moon will be in force and permanent, this paper will discuss the legal and political models available for the mission to and the settlement and development of the Moon.

Looking to the future in space, it is important to analyze the present: there are the now three tiers of space powers (1) the big four--the United States, the Soviet Union, Japan and the European Space Agency (ESA); (2) the emerging spacefarers--China, India, and soon Brazil; (3) the other nations that increasingly rely on space applications such as communications and remote sensing. The first two tiers are interested and able to provide expertise and hardware, and are likely to want to be a part of an international program of space development.

The three most impelling models on which to base international missions to the Moon are the recent U.S./international space station negotiations, the U.S.-U.S.S.R. cooperative agreements, and the more long-standing multi-national space organizations such as Intelsat and Inmarsat. Each model offers useful analogies for various parts of the lunar undertaking. This paper will analyze the best political structure for each stage--the initial base, the growing colony, the expansion to support activities in earth orbit and Mars exploration.

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## COMPOSITE STRUCTURAL MATERIALS FROM LUNAR REGOLITH

The prime key to shortening the time frame  
for lunar base establishment\*

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There appears to be agreement on the premise that transportation costs of the materials of construction to a site in orbit (i.e., space station, SSPS, etc.) from the lunar surface as opposed to the Earth's surface are very substantially lower. This has led to numerous study programs exploring techniques for mining and processing traditional materials for export from the moon to these construction sites. A major obstacle in this approach appears to be the fact that basic aluminum and pig iron are not usable in these forms, but must be further alloyed and processed to give them acceptable structural properties. Both the original mining and smelting along with subsequent alloying seem to call for the transportation of large and complex payloads from Earth to the lunar colony, not only for the initial establishment of the colony but for its later conversion to an exporting entity, as well.

As a result of the data gathered from Apollo missions, it appears that all of the materials needed to produce both reinforcing fibers and matrices for composites are readily available in quantity, first from the lunar regolith and from subsequent mining exploration. Further, it appears that these fibers and matrices could be produced and combined into early colony requirements such as habitats and virtually all necessary structural materials for the establishment of that colony. Studies to date indicate that the original equipment payload to establish this capability could be boosted into Low Earth Orbit easily in a single shuttle payload. Additionally, replication is relatively simple, allowing rapid expansion to an export mode. All of this points to a dramatic reduction in both economics and time required for lunar base establishment and development. This paper will outline current activity in substantiating these parameters.

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## SUBSELENIAN MINING AND HABITATION

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Traditional approaches to lunar base establishment and development have placed facilities on the lunar surface while surface strip mining of the regolith for resource utilization. Principal lunar surface environmental factors impacting on base design, operation, and safety are the radiation levels, vacuum, and temperature gradient. Proposed as an alternative approach for the establishment and development of a lunar base is the placement of the base facilities in subsurface tunnels created as a product of subsurface mining. Subselenian (lunar subsurface) mining and habitation will allow the base to function, on the whole, independent of the threat from radiation to the long term health of base personnel or interruptions to base operations due to solar flares. Potentially, improved productivity and lower cost could be realized over that of surface stripe mining. The technology for performing the tunnelling is investigated with large nuclear subterrenean tunnel excavation system concepts showing the most promise for lunar applications. These devices would melt through the regolith leaving behind glass lined tunnels for later development. The merits and potential of subselenian mining and habitation warrant it receiving more attention and scrutiny in the future as an option for establishing a manned presence on the moon.

# DETERMINATION OF SURFACE TEMPERATURES FOR SP-100 TYPE REACTOR SYSTEMS AS A FUNCTION OF ORBITAL POSITION

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**INTRODUCTION:** Current plans for the exploration and utilization of space indicate that SP-100 type reactor systems will be used to provide electrical power for a wide variety of space missions. One of the most common space missions might involve producing power for a platform or satellite in some kind of orbit about the or moon. For these types of missions, it is important to determine the radiative heat transfer to and from the reactor system as it moves through space. Knowledge of system temperatures is essential, since the safety and reliability of the design depends on an accurate determination of the operating conditions.

**METHODS:** An examination of the basic SP-100 type reactor design reveals that the radiative geometry of the system can be represented as a configuration of distinct components. The simplified reactor configuration consists of several cylindrical and conical sections. The reactor core and electronics/control components, as well as a portion of the power conversion region, can be represented by cylinders of variable length and radius. The reactor shield, radiator, and remainder of the power conversion region can be represented by various truncated cones. View factors can therefore be determined for these simple shapes, rather than for more complex surfaces.

By assuming a simplified orbital geometry, it was possible to determine the view factors from each reactor system surface to every other reactor system surface, as well as the surrounding environment, as a function of orbital position. The environment consisted of the Earth, which was divided into day and night side sections, and black space. The incident solar flux was also determined as a function of the orbital position. With the internal heat generation term for the reactor and radiator surfaces specified, enclosure theory and the Kronecker delta equation were then used to calculate the temperature of each reactor system surface as the satellite moved about the Earth (1).

**RESULTS AND DISCUSSION:** The reactor system surface temperatures were calculated at a large number of orbital positions and altitudes for several reactor geometries and power levels. The results were plotted to produce curves showing the temperatures of various reactor surfaces as a function of orbital position. Typical results depict the radiator temperature of one version of the SP-100 system in geosynchronous orbit about the Earth. When the angle  $\phi$  is zero, the reactor system is directly above the day side of the Earth, at the "high noon" position. A  $\phi$  value of 180 degrees corresponds to a satellite position directly above the night side of the Earth, at the "midnight" position. The major axis of the reactor system passes through the center of the Earth, with the radiator facing the Earth's surface.

At  $\phi = 0$ , the radiator viewed the daylight side of the Earth with the Sun directly behind. As  $\phi$  began to increase, the radiator temperature remained constant at about 777 K. This reflected the fact that for  $\phi$  less than some angle, the radiator surface could not see the sun. The incident solar flux was therefore zero until  $\phi$  increased past some limiting value. As  $\phi$  exceeded 20 degrees, some increase in the radiator temperature was observed because the surface was starting to intercept some small amount of the incident solar flux. The temperature increased steeply between  $\phi$  values of 40 to 80 degrees, as the area of the radiator normal to the solar flux grew. The slope of the temperature increase decreased as the radiator began to view the night side of the Earth, but increased again as the reactor neared the point where it entered the Earth's shadow. The behavior seemed odd, but may be explained by noting that the effective radiator area normal to the incident solar flux is an oddly behaved function of the conical geometry. Upon entering the Earth's shadow, the radiator temperature decreased to a value slightly smaller than the temperature when the radiator was at  $\phi = 0$ , and viewed only the daylight side of the Earth. The result conforms to physical expectations, since the night side of the Earth is somewhat cooler than the day side.

1. Robert Siegel and John R. Howell: Thermal Radiation Heat Transfer, Hemisphere Publishing Company, New York, 1981.

# MODELING OF THE SP-100 REACTOR SYSTEM

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**INTRODUCTION:** CENTAR (Code for Extended Nonlinear Transient Analysis of Extraterrestrial Reactor Systems) is a highly vectorized system modelling code written specifically for the analysis of space reactor systems (1). The first complete reactor power system to be modeled with CENTAR is the SP-100 reactor design.

**METHODS:** The General Electric design of the SP-100 was divided into the following components: nuclear reactor core, general piping, thermo-electric pumps, heat exchangers, accumulators, and radiators. The reactor core was modeled using a combination of the generalized pipe, fuel rod, and plenum components in CENTAR, while the radiator was modelled as a generalized pipe component. The reactor core model consists of an outer channel surrounding the core, with three inner channels containing the fuel rods. These channels are connected by inlet, outlet, and mixing plenum components.

A total of three axial cells have been specified along the length of the reactor core. The thermo-electric pumps have been divided into 4 computational cells, and the heat exchangers have been divided into 5 computational cells. Most of the piping segments in the system have been divided into 2 or 3 computational cells, while the radiator has been described by 15 computational cells. Accumulators are divided into 3 computational cells. The twelve loops in the actual SP-100 design were collapsed into two loops to simplify the input deck, but the overall system mass and power levels were unchanged.

**RESULTS:** The first CENTAR results for the SP-100 system describe the temperature distribution at several points in the primary and secondary loops as the reactor system undergoes a transient in which the reactor scrams from steady-state, full power operation. For this simple calculation, the transient was assumed to occur so soon after startup that decay heat from the reactor core could be neglected. In addition, only 10% of the radiator area was assumed to remain functional. The problem was further simplified by assuming that the fluid loops were at a uniform temperature at the start of the transient.

**DISCUSSION:** As expected, the fluid temperatures in the secondary loop dropped sharply with time, as energy was lost from the system through radiation to space. The radiator inlet and outlet temperature were equal at the start of the transient, but clearly diverged as the cool-down progressed. Conduction in the secondary loop, as well as losses through radiation, acted to establish the expected temperature gradient within the loop. The temperature of the primary loop also began to decrease as energy was lost from the system, but the rate of loss was much less than in the secondary loop. The result reflects the fact that the only mechanism for heat removal from the primary loop was through heat transfer between the primary and secondary sides of the reactor system. Since the driving force for this heat transfer was the temperature difference between the primary and secondary sides, it was expected that the temperatures in the secondary loop would decrease at a much greater rate than the temperatures in the primary loop during the initial stages of the transient.

With the SP-100 reactor system completely modeled, CENTAR will be used to examine the behavior of the power system for two transient cases. First, the start-up of the SP-100 reactor power system will be analyzed. Starting with the reactor at zero power and with the entire system at a low uniform temperature of 523 K, a ramp reactivity insertion will be used to bring the reactor core up to full power. The analysis will continue until all temperatures and pressures throughout the system have reached their steady-state values. The second transient examined by CENTAR will be a loss of heat sink event. With the reactor system operating at steady-state and full power, a large fraction of the radiator surface will be removed. The resulting transient response and reactor scram will then be observed until a point of relative stability is reached. Future work will include the examination of loss-of-coolant events initiated by meteoric bombardment of the system, particularly in the radiator component. Transients resulting from damage to or malfunction of the thermoelectric pumps, heat exchangers, accumulators, and general piping will also be analyzed.

**CONCLUSION:** In its present form, the model currently used with CENTAR is the most detailed computational model of the entire SP-100 reactor system ever developed. Researchers at the University of New Mexico (UNM) have assembled and successfully tested an SP-100 systems model. However, the model consists of a single loop and represents most components as a single computational unit. Although the reactor core and radiator components are examined in more detail, the level of detail utilized in the CENTAR model of these components is still greater. In addition, the UNM model is quasi-steady state in nature and is therefore somewhat limited (2). CENTAR, in combination with the current two-loop model, is therefore the most advanced method yet developed for simulating the SP-100 reactor system.

1. B. Nassersharif et. al. , ANS Winter Meeting, Los Angeles, California, November 15-20, 1987.
2. A. Parlos, Personnal Communication, Texas A&M University, College Station, Texas, June, 1987.



## Production of Large Telescopes and Mirrors From Moon Materials

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A number of prior studies have dealt with the advantages of large scale astronomical instruments and arrays on the Moon. Also, an ultra large baseline array that suggests itself is a combined Moon-space "dish" of the Moon and the libration points  $L_1$  and  $L_2$ . A "halo orbit" around  $L_2$  furthermore offers the additional advantage that any satellite in it will always maintain a line-of-sight contact with the earth and the Moon's far side. The capability to volume produce and deploy large astronomical instruments inexpensively on the Moon would not only hasten development of Moon-based array systems, but would also afford world astronomers expanded Moon-based viewing opportunities.

The concept of Moon-based mining combined with either Moon- or space-based fabrication promises to provide a means for the desired inexpensive volume production. The obvious advantages of the suggested production concept are: relatively inexpensive materials; lessened stresses on large structures because of reduced gravity environments; and lessened launch costs. The lunar and space environments furthermore offer opportunities for unique processing and fabrication techniques that should allow unique or superior products. For example, volume production of large mirrors should be easily accomplished in space or in a lunar environment by a variation of a replication technique that was suggested previously for large scale production of moderately large earth mirrors. In this technique a master mold is prepared. The optical surface of the mold is the inverse of the surface desired and is prepared by polishing. The mold surface is then coated by vapor deposition with a mold release material. Subsequent films or coatings are vapor or sputter deposited. After the deposition processing, the reflective shell is released from the mold. The vacuum environments of space or on the moon would allow large controlled vacuum volumes where the described coating operations could be conducted. Also, the low gravity forces of these environments would allow much larger shells than would be possible on earth.

The possibility of floating large liquid masses in lunar orbit raises the prospect of forming large glass lenses of various shapes with smooth surfaces without the necessity of grinding and polishing operations. For example, a liquid mass, freely floating, will assume a perfectly spherical shape because of surface tension forces. Solidification of such a liquid mass in low-g to form surfaces without bulges and ripples would require that prior to solidification all body oscillations be damped out and that viscous forces be sufficient to overcome surface tension forces leading to surface rippling because of thermal gradients. Molten glass, being inherently a liquid of high viscosity, appears to be an ideal candidate for such processing. The capability to float molten glass will also allow direct production of unique lenses. For example, it has been suggested that a sphere of optical glass surrounded by an outer shell of another glass of much lower refractive index would be a very good approximation to a perfect lens for infrared and microwaves.

The presentation will briefly consider some possible lunar- or space-based astronomical instrumentation and systems. Also considered will be the means to obtain optical quality glass, ceramics, and metals from lunar soil as well as various processing techniques to produce large scale lenses and mirrors on the Moon or in space.

## A COMMONALITY ASSESSMENT OF LUNAR SURFACE HABITATION

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This paper presents a commonality assessment of lunar surface habitation. Thus far, NASA has baselined the space station common module for initial lunar base habitation; however, nothing beyond definition has been done. This paper extends the NASA baseline beyond the definition phase by providing a parametric habitation study involving the current common module design. In addition to assessing the adaptability of the space station module to the lunar environment, analyses of key supporting systems are also presented. These systems include environmental control and life support systems, active thermal control systems, and radiation protection. A matrix modeling methodology is utilized to define the design requirements and attributes of the systems. The model pays particular attention to the parameters of volume, mass, power requirements, and waste heat generated.

The viability of the space station module design depends upon the adjustment from a zero gravity environment to a 1/6 Earth gravity environment on the Moon. Alterations of interior space to a standard floor/ceiling configuration and application of minimum volume standards are used to outfit the module. With a variable crew size ranging from three to eight persons, the parametric/volumetric analysis provides resizing of the module as a function of crew size. An extension to the module's length rather than its diameter is undertaken in order to provide more useful space. Impacts on launch vehicle payload capability are also presented.

This paper discusses four possible environmental control and life support systems for crew air and water supply. The systems vary according to cycle closure, ranging from open to partially closed to closed (including supercritical water oxidation). Trade studies provide comparison between systems according to the key parameters, as well as resupply mass and maintenance time. The active thermal control system incorporates the acquisition, transport, and rejection of waste heat generated by the module equipment. This paper defines a two-phase water loop internal to the module which interfaces with a two-phase ammonia loop external to the module for the acquisition and transport functions. Three heat pipe radiator configurations are presented for heat rejection, including full view, rotating, and with a canopy. The need for radiation protection on the lunar surface to enable human inhabitation is also presented. With respect to mission duration and allowable dose equivalents, the burial of the habitation module is analyzed. Construction requirements for module emplacement are also presented.



EFFECTS OF LONG-RANGE RECRUITMENT GOALS ON THE  
FEASIBILITY OF OPTIMUM CREW COMPOSITION: MARRIAGE AS NEEDED  
OFF-THE-SHELF TECHNOLOGY FOR SOCIAL ENGINEERING IN LONG-DURATION  
MISSIONS IN ISOLATED AND CONFINED ENVIRONMENTS. B.L. Halliwell,  
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Productivity of small crews in isolated and confined environments for several months or years will depend in part on how well group interactions help meet members' psychological needs rather than aggravating effects of stress from mission tasks and risks, boredom and loneliness, and irritants of close confinement with others in the hardware environment. Relevant studies demonstrate that after the first few months, dilemmas in group dynamics, socioemotional needs in work-group life, and individual R and R needs will press hard against the limitations of a habitat module far from Earth--especially since stresses will become cumulative.

Therefore much research on "soft human factors" is needed. But it is unlikely to be done, and even if it were available, limitations on control over crew preparation and multiplicity of variables would reduce reliable application. A sound shortcut, achievable with resources available, lies in assembling crews for such missions using psychologically self-sustaining dyads, because crew preparation can focus on helping such marriages and resultant crew dynamics become able to neutralize mission stresses.

The crucial requirement of the policy is sufficient numbers of personally and technically qualified couples. Long-term social changes conducive to formation of increasing numbers of dual-career, childless couples can be built upon within the space-technology community if in the near future NASA enunciates pro-couple recruitment policies for the moonbase and Marsflight crews needed 20+ years hence and begins organizational movement in that direction. The cost-free avenues for implementation of this policy and the P.R. advantages to NASA can override resistance to innovation caused by fiscal duress and attitudinal obstacles.

The main obstacles to the policy are attitudes in the social and the organizational-subcultural environments -- regarding sex, women, and marriage. Some of these are not truly relevant, and some are losing social acceptability due to proven invalidity.

But some, correctly analyzed, are in fact part of the situation which makes the policy more advantageous, if implemented using sound procedures. Selected examples: (1) Past refusals to consider "sex" a "problem" on long missions derive from subcultural attitudes which developed to meet different circumstances, and this position is valid only in that sexual tensions are indeed controllable as long as mental health is unimpaired. But stress not relieved in sanctioned ways may find forms of relief which cause conflict, threatening group functioning, and women perceived as available become focal points of this process. Risks of such conflicts can be so reduced that demonstrated benefits of including women outweigh them; withdrawal, the preferred reaction to excessive stress among all-male crews, may be just as lethal to crews in harsh, isolated environments. (2) Negativism regarding marriage as the primary delivery system for the basic psychological requirements is derived from non-analogous experiences. A crew can easily learn to cultivate norms which help it to sustain its wellbeing through nurturing of its members' marriages.

EXERCISE AND THE MUSCULOSKELETAL SYSTEM:  
FUTURE CONSIDERATIONS FOR EXTENDED SPACE FLIGHT

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BIOMEDICAL STUDIES FROM U.S. AND SOVIET SPACE MISSIONS HAVE CLEARLY DEMONSTRATED THE ALTERATIONS IN THE MUSCULOSKELETAL SYSTEM DURING LONG DURATION SPACE FLIGHT. THE EFFECT OF 0-G ON THE MUSCLE IS EXHIBITED BY MUSCLE ATROPHY AND LOSS OF MUSCLE STRENGTH. IN BONE, THERE IS DEMINERALIZATION RESULTING IN A NEGATIVE CALCIUM BALANCE. THE ETIOLOGY APPEARS TO BE THE DECREASE IN ACTIVITY AND EFFECT OF GRAVITY ON THE MUSCULOSKELETAL SYSTEM. THESE CHANGES IN THE BONE AND MUSCLE METABOLISM MAY PRESENT THE MOST PROFOUND MEDICAL DISTURBANCES FOR CONSIDERATION OF EXTENDED CREW STAYS FOR THE SPACE STATION AND LUNAR BASE.

THUS, EXERCISE WILL PLAY A SIGNIFICANT ROLE IN STABILIZING OR PREVENTING THE MUSCULOSKELETAL RESPONSE TO 0-G. THE SKYLAB STUDIES HAVE SHOWN THAT EXERCISE CAN BE INSTITUTED IN THE MICROGRAVITY ENVIRONMENT. IN THESE STUDIES, THE USE OF THE ERGOMETER AND TREADMILL PARTIALLY PRESERVED MUSCULAR ACTIVITY AND RANGE OF MOTION BUT, THE EFFECTS ON DEMINERALIZATION IS UNCLEAR. DEVISING AN EXERCISE PRESCRIPTION USING SEVERAL MODES OF EXERCISE WILL BE MOST USEFUL IN MANAGING THE MUSCULOSKELETAL SYSTEM DURING LONG DURATION SPACE FLIGHT.

**SYSTEMS DESIGN FOR A LUNAR CULTURE AND PERSONNEL DEPLOYMENT.** Philip R. Harris, Ph.D., Living Systems Co-Investigator/Senior Research Associate, California Space Institute, (A-021, UCSD), LaJolla, CA 92023

The establishment of a lunar base can become a prototype for future space settlements. It is an opportunity to develop a learning laboratory in space living. The return to the Moon on a permanent basis will be marked by long duration missions, increased size and heterogeneity of crews, and complex challenges requiring more diverse competencies. The lunar pioneers will create a unique cultural world with its own internal dynamics, practices, and norms. To ensure lunar survival and quality of life, technological capability needs to be integrated with behavioral science insights and methodology. Multidisciplinary systems research is now being directed toward broader human factor issues of space habitation, such as, the physical, psychological, sociological, cultural, financial, political, legal, educational, and managerial, as well as information processing and communications exchange.

For the past thirty years, humankind has unconsciously been creating a space-based culture. Although the data base on space habitation is relatively small, the process accelerates as both Soviet and American space stations employ rotating crews in extended space flight. For the first time in human history, it is possible in advance to design systems for lunar culture and personnel deployment that are in harmony with a unique location and environment, such as the Moon. Contemporary anthropological models may be applicable to this emerging "free-fall" culture, permitting systematic analysis of potential characteristics of lunar dwellers. One paradigm for this purpose would examine their sense of identity in space; relationships and family; communication and language; values and norms; dress and appearance; beliefs, customs, and traditions; food and feeding habits; mental processes and learning; work habits and learning practices.

Before massive space migration and colonization occurs, a Moonbase would enable NASA planners systematically to address relocation issues there with a limited number of spacefarers to that remote and hostile environment. As part of research at the California Space Institute on the Application of Living Systems Theory, this investigator has begun the study of terrestrial experience and behavioral science literature on people deployment to polar regions, nuclear submarines, offshore rigs, and varied multinational assignments abroad. The survival and acculturation of the first Moon inhabitants could be enhanced by transfer of insights from these analogs, especially in Antarctica, so as to delimit "space cultural shock" and further more effective lunar performance.

Since the extraterrestrial population will eventually go beyond elite astronauts and cosmonauts, a space personnel deployment system should be designed for intercultural preparation and evaluation research that would be applicable to future generations of spacefarers. Foreign deployment studies indicate to this investigator that this may be centered around four components:

- (1) assessment, so as to select the most suitable candidates to go aloft by ascertaining their level of coping skills and psychological adjustment, while screening out potential misfits who jeopardize themselves or others' well being.
- (2) orientation before departure through programmed self-learning and training to prepare personnel for extended spaceflight and life beyond this planet.
- (3) onsite support and monitoring, both physical and psychological, to facilitate acculturation and group living within a space community.
- (4) re-entry policy and programs to deal with relocation back to the home planet and successful acculturation once again to gravity living. To discover the effects of long-duration missions in space on the body, mind, and spirit, information for further study and analysis should be gathered systematically from the returning "expatriates." Thus, it may be possible to improve recruitment, selection, and training for the expanded human "passover" from Earth's boundaries.

LUNAR HYDROGEN FOR PROPELLANT; L. A. Haskin, Dept. of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130

Economics of the use of lunar oxygen as oxidizer in near-Earth space should be enhanced if enough lunar hydrogen were also available to fuel near-Earth operations or at least to fuel the transport of oxygen to low-Earth orbit. Concentrations of hydrogen, very low in all lunar materials, are highest in fine material from the regolith, where hydrogen has been implanted by the solar wind. A target number for oxygen use is 300 tonnes/year. The corresponding mass of hydrogen is about 40 tonnes/year for the stoichiometric mixture (but not necessarily for the optimum burn mixture). At typical concentrations of about 50 micrograms hydrogen per gram of mature regolith, this corresponds to the amount of hydrogen in some  $8 \times 10^5$  tonnes of lunar fines. This would require extraction of hydrogen from 6,700 tonnes of fines per day, a volume of about  $3,800 \text{ m}^3$ , if operations were possible for 120 24-hour days/year. This material would have to be handled twice, once to haul it to the extractor and once to remove it. If the regolith is used to a depth of 1 m, the area to be excavated and refilled per day is about  $8,000 \text{ m}^2$ , or the upper regolith within a radius of 380m of the extraction plant. A dirt mover travelling at 6 km/hour would have to handle about  $19 \text{ m}^3$  per trip, a mass of 33 tonnes, but a weight of only 5.5 long tons.

The material must be heated to  $700^\circ\text{C}$  to extract most of its hydrogen. If 80% of the heat were recovered by absorption in the subsequent batch of material, about 12 megawatts of power would be required. This corresponds to the sunlight falling on about  $7 \times 10^4 \text{ m}^2$ ; at 50% efficiency of use, this corresponds to an area  $375 \text{ m} \times 375 \text{ m}$ . The sunlight might be concentrated by mirrors, or converted to a form such as microwaves that is more readily distributed throughout the volume of soil being heated.

If the processing chamber had a cross section of  $1 \text{ m}^2$ , it would need to be some 26 m long to accomodate the required flow of lunar material. Although the concentration of hydrogen is low, the pressure of it plus other gases at  $700^\circ\text{C}$  is nearly 10 atmospheres, enough to drive a turbine to help stir the system and aid in heat transfer. In a continuous-feed system, the entering lunar fines themselves might serve as an effective barrier to escape of gas out of the entry port if the system was operated at a pressure below 0.5 atmospheres.

Pyrolysis would yield a mixture of useful gaseous products, including  $\text{H}_2\text{O}$ ,  $\text{H}_2\text{S}$ ,  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{NH}_3$ ,  $\text{HCN}$ , and noble gases. The most effective means of obtaining hydrogen might be to burn the mixture of gases in lunar oxygen, separate water, and store and transport the hydrogen in that form for electrolysis at the site of its use.



ELECTRODE REACTIONS AFFECTING THE EFFICIENCY OF OXYGEN AND IRON PRODUCTION BY ELECTROLYSIS OF LUNAR SOILS; L. A. Haskin, K. W. Semkow, D. J. Lindstrom, and R. H. Lewis, Dept. of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130

Oxygen, iron metal, and silicate melt of altered composition are easy products to make by electrolyzing molten lunar soil. Electrolytic efficiency will depend on the conductivity of lunar silicate melts; heat instead of products is produced by that portion of the electrical energy required to overcome the resistance of the melt. Conductivities of some molten lunar soils are high enough for reasonable cell design. Conductivities depend on the mobility of the ions that carry the current through the melt. Intrinsic mobilities of ions are measured in experiments using high-frequency (10 kHz) alternating current. If the frequency of the alternating current is decreased, separation of cations from anions within the melt becomes sufficient to polarize the melt and this raises the resistance until the flow of current is halted, unless the potential is high enough to discharge ionic species at the electrodes. Practical electrolysis requires direct current through polarized melts.

Direct current conductivities for iron-bearing silicate melts are anomalously high, not showing the expected, strong decrease from alternating current conductivities that calcium and magnesium silicates show. Some investigators have suggested that this results from electronic conductivity through melts containing transition metals. If so, a substantial fraction of the current would produce no electrolysis product and the efficiency of the process could fall below practical levels.

Our experiments show that electronic conduction is not the cause of this anomalous conductivity. The magnitude of change in conductivity of addition of FeO to silicate melts is the same as that for addition of equimolar amounts of MgO or CaO. We find no cutoff potential below which the high direct-current conductivity stops, as expected for a semiconducting melt. We find the efficiency of electrolysis to produce iron metal to be at least 60%, far above the few percent implied by the anomalous value for the conductivity. The reason for the anomalous conductivity is the oxidation of some  $\text{Fe}^{2+}$  to  $\text{Fe}^{3+}$ , which decreases the efficiency of electrolysis, but not drastically. This process competes with oxidation of oxide to produce oxygen gas. Production of oxygen gas requires a high enough potential to break down polymerized silicate, because the concentration of oxide ion in these melts is very low (about  $10^{-5}$  mols/liter). That process is favored by overvoltage, and overvoltage is required in any event because the conductivity of even iron-bearing silicate is relatively low. We have not measured the efficiency of oxygen production, but we observe abundant bubbles in quenched charges from electrolysis. Thus, direct electrolysis appears to be efficient enough to deserve further study as a practical means of obtaining lunar oxygen.



### "Life Systems for the Lunar Base"

Phillip B. Hawes, Architect, Sarbid Ltd.

Mark Nelson, Chairman, Institute of Ecotechnics

The paper gives an overview of biospheric research currently underway at the Biosphere II project of Space Biospheres Ventures near Tucson, Arizona and its application to lunar base life support systems.

Biosphere II is designed to be an energetically and informationally open and materially enclosed life system covering some 2 1/2 acres. Variable volume apparatus connected to the structure accommodate differences in pressure between Biosphere II and ambient conditions. Energy will be supplied by photovoltaics and co-generation, and cooling is assisted by use of solar ponds. It will contain intensive agriculture area and human habitat as well as "wilderness areas" - rainforest, savannah, desert, marsh and ocean, and will support some 3000 species plus microorganisms. It will provide full nutrition and water/air cycling for a crew of 8 "biospherians" who will live inside for an initial experimental closure of two years, commencing late in 1989. The crew will monitor and manage Biosphere II.

Currently in operation is a 450 cubic meter test module, used for experimenting with biological systems and is of a scale suitable for early stages of lunar life support.

Aspects of unique lunar resources and constraints in designing, building and operating a lunar base life-support system which are addressed include: methods of utilizing lunar materials for construction and soil building; energy sources; atmospheric pressure, radiation and temperature range; behavior of small task groups in isolated circumstances.

The paper outlines a phased approach to the creation of closed ecological life support on the Moon. It draws on the experience generated from operation of the test module and the project's Biospheric Research and Development Complex which are operating prototype intensive agricultural systems.

**GEOSCIENCE INVESTIGATIONS CONDUCTED FROM A MANNED LUNAR BASE.** B. Ray Hawke<sup>1</sup>, Paul D. Spudis<sup>2</sup>, and Mark J. Cintala<sup>3</sup>; <sup>1</sup>Planetary Geosciences Division, HIG, Univ. of Hawaii, Honolulu, HI 96822; <sup>2</sup>U.S. Geological Survey, Flagstaff, AZ 86001; <sup>3</sup>Advanced Research Projects Office, NASA/Johnson Space Center, Houston, TX 77058.

There are many compelling reasons for lunar geoscience investigations. Chief among these is the fact that the Moon is a baseline for understanding planetary surface processes as well as the early history and evolution of the terrestrial planets and many satellites of the outer planets.<sup>1</sup> The Moon possesses a differentiated crust as well as an ancient surface that has been well preserved since very early in solar system history. These characteristics and the Moon's relative accessibility make it an advantageous laboratory for investigating the early history of the inner solar system.<sup>1</sup> The Apollo missions acquired data that without question revolutionized lunar and planetary science.<sup>2</sup> Although considerable understanding of planetary surface processes has been achieved using the Apollo database, a number of fundamental problems such as 1) lunar crustal structure, composition, and petrogenesis; 2) geologic history; and 3) mantle composition and heterogeneity, remain only partly resolved.

A number of unmanned lunar missions have been proposed as precursors to a manned lunar base.<sup>1</sup> The Lunar Geoscience Observer mission will almost certainly be flown prior to the establishment of a lunar base. Other missions (e.g., Global Surface Geophysical Network; Sample Return Mission) may be conducted in support of the specific goals and objectives of the lunar base. Still, while the results of these missions would undoubtedly produce a major advance in lunar science, it is unlikely that the majority of the critical questions can be answered in a satisfactory manner. The purpose of this paper is to identify and discuss the problems which will be solved by geologic studies supported by a lunar base.

Impact cratering is a fundamental planetary process of great importance. The manned lunar landings and returned samples generated great interest in impact cratering processes. Subsequently, major advances were made in our understanding of cratering mechanics and processes due to theoretical and experimental cratering studies, as well as detailed investigations of terrestrial impact structures, and analysis of the lunar samples. Still, many questions remain unanswered. While studies of terrestrial impact craters will continue to be useful, the highly eroded state of large terrestrial craters and the fact that they formed in a terrestrial environment will limit their utility. The proposed lunar base will allow field studies and sampling of impact structures which range in size over several orders of magnitude. Small, fresh impact craters will be present in the immediate vicinity of the lunar base. Expeditions supported by the lunar base will be necessary to investigate a variety of large craters. Such a traverse across the Imbrium-Procellarum region was described in detail by Cintala *et al.*<sup>1</sup> The major problems to be addressed include the following: 1) the modes of ejecta emplacement (i.e., ballistic transport, base surge, surface flow, etc.), 2) the distribution of impact melt in and around craters as a function of size, 3) the depth of origin of the various ejecta units, and 4) the nature of the crater modification processes.

Special attention will be paid to the lunar multi-ringed basins since these large impact structures have played such a dominant role in controlling lunar surface morphology and composition. Absolute ages for these basins can be determined by radiometric dating of their melt deposits. This information is critical for deciphering the early cratering history of the Moon.

Volcanism has also played a major role in the geologic evolution of the lunar surface. While much has been learned by intensive geochemical and petrologic studies of the returned mare basalt samples as well as recent photogeologic and remote sensing investigations<sup>3,4</sup>, many key questions regarding lunar volcanism remain unanswered. These include the duration and extent of mare volcanism, the role of early mare volcanism in controlling crustal composition, and the composition of mare basalt source regions. The nature and relative importance of highlands volcanism is also poorly understood.

Finally, investigations conducted from a lunar base will be necessary to determine the origin and stratigraphy of the lunar crust. The petrogenesis of the crustal rocks and the structure of the highlands crust are of critical importance.

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CREATING A LUNAR FACILITY:  
THE 1988 DESIGN PROJECT OF THE  
INTERNATIONAL SPACE UNIVERSITY™

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This paper describes the International Lunar Facility (ILF) Design Project of the 1988 Summer Session of the International Space University (ISU), which will take place over nine weeks at the Massachusetts Institute of Technology (MIT). The ISU Design Project will involve the participation of an expected 100 international graduate students attending the ISU, guided by an expert team of advisors and a Design Project Director. The ILF will also be the focus of the eight multidisciplinary courses taught during the Summer Session.

The International Space University is a project of the Space Generation® Foundation and was established during a three-day Founding Conference held in April, 1987, at the Massachusetts Institute of Technology. The outline for the ILF Design Project was developed following the ISU Founding Conference and is expected to occupy approximately 40% of the students' time during the 1988 Summer Session. Professors, technical experts, and other support staff from NASA, ESA, Canada, and other nations will help the ISU student body develop and prepare a Final Report on the International Lunar Facility.

It is expected that teams of seven ISU students will spend part of each day with faculty working on advanced concepts in their specialty areas. Eight disciplines (policy and law, satellite applications, human performance in space, space manufacturing, management and business, arts and architecture, space sciences, and space engineering) will be integrated by the participants into the ILF Design Project. Groups will begin with an ILF baseline configuration, then develop the specific technical, scientific, political, legal, and managerial aspects of the ILF.

A Final Report on the ILF, based on the top recommendations of the groups, will be prepared by the student participants in the final days of the Summer Session. The ILF scenario presented in the first year may be enhanced in each of the four following Summer Sessions. The ISU will be hosted by different major international institutions of higher education through the 1992 International Space Year, at which time its curriculum and projects such as the ILF may be expanded into a full-year, degree-granting educational format.

ADVANCED PROPULSION FOR LEO - MOON TRANSPORTATION: IV.  
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In order to gain insight into the benefits of new transportation technologies, a simplified computational model of the LEO - Moon transportation infrastructure has been developed. A reference transportation infrastructure, based upon near - term technology developments, is used as a departure point for assessing other, more advanced technology alternatives. A comparison of the benefits of technology application, measured in terms of propellant mass payback ratio (MPR), suggests that several of the advanced technology alternatives could result in substantial improvements in the efficiency of LEO - Moon transportation systems.

The reference transportation infrastructure in this model presumes fruition of certain technology developments for reusable Orbit Transfer Vehicles (OTVs), OTV-derived lunar landers, space-based OTV accommodations, and the lunar surface base. Key OTV technology in the reference case includes aerobraking, advanced O<sub>2</sub>-H<sub>2</sub> engines, and lightweight structures. Technology for space - based OTV servicing at an Orbital Transfer and Staging Facility (OTSF) includes telerobotic maintenance, zero - g propellant transfer, and automated rendezvous and docking. The largely self-sufficient lunar base produces liquid oxygen propellant for the OTV and lunar lander. In order to utilize this lunar oxygen most effectively, the lunar lander uses an engine with a high O/F ratio.

These technology advancements allow the reference transportation system to achieve an MPR of ~1, i. e., the system can deliver about as much lunar oxygen (or other lunar materials) to LEO as the mass of reagents, hydrogen fuel, and spare parts required from Earth to produce and transport lunar oxygen and maintain the infrastructure. The MPR then serves as a figure of merit for considering other alternatives which use more advanced technology. MPRs for some of the new technology alternatives are high enough to suggest that these technologies should play a major role in future lunar operations.

The advanced transportation technology alternatives chosen for comparison through the model have included mass drivers, tethers for momentum transfer, ion engines, and laser propulsion. These alternatives were first analyzed separately, as incremental modifications of the reference configuration, then selected promising options were combined. System parameters for configurations using these technologies were determined through the interaction of a team of academic, government, and industry representatives, resulting in representative alternative configurations which could be analyzed in the transportation model. An analysis of these configurations indicates distinct advantages for several of the options, suggesting that the reference architecture should be modified over time to make use of advances in these areas.

In order to reap the benefits of such advanced technology options early in the development of permanent lunar operations, exploratory research and development is required in the near term. It is hoped that the analysis reported here will give impetus to the planning for lunar transportation infrastructure evolution, and to the timely development and implementation of such new technology alternatives.



## LUNAR AGRICULTURAL "SOILS"

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A major component of a Lunar Base Controlled Ecological Life Support System (CELSS) will be the growth of plants; primarily for food but also for the psychological aspects of an Earth-like environment with trees, grass, flowers and normal intensities of sunlight. A bioregenerative CELSS has its greatest application at a lunar or planetary base, where area, volume, mass, thermal and power restrictions are likely to be less limiting than on board a space vehicle. Instead of resupplying food to Space Station(s) from Earth, resupply it by way of lunar base agriculture since the Moon's gravity (1/6th that of Earth) will reduce transportation costs. Furthermore industrial and metabolic wastes from Space Station could be returned to the lunar surface where they could be re-cycled; thus it becomes a resource available to lunar base expansion rather than a liability for Earth return via Shuttle. Manned interplanetary spacecraft will be extremely large vehicles requiring on-orbit assembly and supply due to their long-duration missions. Initial supplies of food could be provided from lunar base agricultural production. Waste products from returning manned interplanetary spacecraft could be sent to the lunar surface for renovation and use.

Growing higher plants at a lunar base will require examination of many physical, chemical, mechanical, and biological areas to achieve maximum production. Soil physical parameters such as texture and structure affect fluid (air and water) movement and heat transfer within a soil. The effects of the reduced gravity of the Moon on development of soil structure and the physics of fluid movement in the soil due to gravity and capillary action must therefore be examined. Biological aspects involve selection of the plant species and mixes to satisfy nutritional needs. Whether or not to introduce a microbiological population into the soil as well as what types of organisms for specific purposes will need to be examined. Many experiments, both terrestrial and at a lunar base installation, involving genetic engineering or biological selection of both plants and microbial species are envisioned. These experiments will involve adapting plants to the reduced lunar gravity where structural components of the plant, such as the stem, can be reduced while increasing the size and number of the fruit produced. Selection of bacterial species to renovate or remove a specific element from waste materials by converting it to a harmless compound or by incorporation into cell biomass are examples of needed research. Chemical areas requiring examination include the extraction of essential plant growth nutrients from the lunar material, removing any toxic elements or compounds from the soil, controlling the soil pH, etc. Additionally, the use of soil in renovation of waste substances must be investigated. A host of mechanical attributes of a lunar farm (such as automation of planting and harvesting of crops, and remote sensing of crop condition) must be addressed. Artificial intelligence and smart systems technology needed for control and operation of a lunar agricultural operation are technological areas which require extensive development.

A lunar farm would not have to be transported from the surface of the Earth. The basic materials required for soil are already there, in the form of regolith. Materials imported from Earth to the Moon would be limited to those constituents needed in only small quantities. There are a number of lunar resource reclamation schemes to get metals and elements out of the regolith. Nutrients could then be added to a regolith slag or spoil material to form a regolith-derived soil. It appears technologically feasible to develop a lunar base agricultural industry which can support all human activities in space for decades to come.



PREFABRICATED FOLDABLE LUNAR BASE MODULAR SYSTEM  
(HABITATS, OFFICES, AND LABORATORIES)

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In spite of the advanced building technologies available today, concepts for mobile architecture are still limited to certain styles and applications. The need for temporary housing for pilgrims to the holy city of Makkah, Saudi Arabia, required the development of multi-story foldable mobile structures. As a project, however, it is styled in such a manner as would open new horizons for an exclusive type of mobile architecture, characterized by its own individuality and devoted to special purposes. As a result, different types of mobile architectural applications were realized and proposed.

In the context of lunar settlement, most ideas anticipate great construction operations, great volumes and weights of materials, heavy and complex lifting mechanisms, and elaborate site preparations. In the view of the high cost of transport and site work in an irradiated near vacuum environment, the first habitat and work station on the lunar surface undoubtedly has to be prefabricated, self-erected, and self-contained. Launched, compacted to the minimum size, it has to provide the maximum habitable and usable space possible on the moon. For this purpose, the concept of multi-story foldable mobile structures is developed further.

A lunar modular foldable system of habitats, offices, and laboratories is proposed to be prefabricated, pre-assembled, launched, self-erected, self-protected, and self-adjusted to the site. It is thought to be well suited to the lunar environment, where manual construction and site preparation may be difficult and galactic radiation flux protection is essential. The typical lunar base module is a cylinder of 11 meters in diameter and 33 meters in length connected to a lunar shuttle vehicle. Upon landing, the shuttle vehicle will separate while the cylinder will longitudinally open in two hinge connected halves. Each half contains four foldable structures arranged in a way that each two will form a pair and lean against each other.

Needless of any lifting facilities and depending on lunar gravity, the cylinder has its own mechanism and hydraulic footing system to open and maintain site self-adjustment, horizontality and stability. Following the self-unfolding of the five story structures, enclosures of single rooms are provided by lightweight wall panels, unfolded from ceilings, creating conventional architectural spaces suitable to the 1/6 gravity environment.

Two layers of pneumatic structures embedded between the two halves of the cylinder and fixed around, will be inflated leaving a 2 meter space for ground regolith to be pumped in. This concept of regolith-stuffed pneumatic structures shielding, while supported by, the erected skeleton is another approach to utilize local resources for solar flare radiation protection. The infrastructure and utility systems are designed for greater convenience and complete self-sufficiency.

The modularity of the system and the concept of the lunar shuttle vehicle to transport typical base modules are meant to create an interconnected network of complexes providing a great variety of agricultural, industrial, medical, and social applications for the future lunar city.

Evolving from the same philosophical approach of space settlements (i.e., space stations), it is suggested in this attempt that such a prefabricated self-contained system, providing all necessary life-supports, is most appropriate for the very initial stage of lunar colonization and manned settlement.

## A VARIABLE FORCE CENTRIFUGE ON THE LUNAR SURFACE

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The prospect of a manned lunar base brings with it exciting possibilities for basic research in many fields of endeavor, ranging from selenological studies to the Search for Extraterrestrial Intelligence. Perhaps the greatest opportunities are to be found in the life sciences, with results that could have far-reaching implications as mankind continues its drive outward from its mother planet.

It is now generally accepted that a piloted mission to Mars is on our spacefaring agenda. The raw technological expertise is essentially available; what is not so immediately forthcoming is knowledge required to support the well-being of a human crew. American experience is restricted to that gathered from short to intermediate crew stay times in a microgravity environment. Soviet data, while covering much longer exposures, is still limited. Absolutely no one has data on crew responses to gravitational levels between zero-G and one gravity, as would be found on the Moon and Mars.

Centrifuges on orbiting spacecraft could provide a means of simulating fractional gravity. However, current Space Station design limits the size of any internal centrifuges to, at most, several meters. This precludes their use as a means of exposing humans to extended periods of variable gravity. While the Space Station will provide data on long-term exposure to micro- and fractional gravity environments by utilizing small experimental plants and animals, such information will be limited in scope until such time as a large variable force centrifuge is in operation in space.

It has been suggested that exposing astronauts to centrifugal force during long space missions might ameliorate some of the undesirable aspects of microgravity exposure. It is still uncertain whether such "artificial" gravity can serve as a long-term substitute for the real thing. Further, no one has any data pertaining to the ability of a crew to function in fractional-g environment after exposure to long-term spaceflight (regardless of what countermeasures are used). Placing a large variable force centrifuge on the lunar surface might be easier than building a facility in space. Such a lunar facility could provide an opportunity to study centrifuges as both a countermeasure to microgravity-related health problems and as simulators of long-term exposure to Martian gravity.

### **Training for 21st Century Space Missions**

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The development and execution of space missions in the 21st century will create a need for new and daring approaches to prepare and educate the people who will take part in those activities. Mission scenarios will be totally different from any previous programs. Mission durations will be greater. Isolation and distance from Earth will exceed past experience. All of these circumstances will affect the manner in which education and training are designed and executed.

New types of training will be developed including training performed onboard the space vehicle. This might be conventional or embedded in the actual flight equipment. It could also include video lessons transmitted from the Earth. The extended durations of the flights will make it imperative that objective evaluations of the flight crew be carried out in flight. These evaluations could have a bearing on what extra training is mandated for that crew while they are still in flight. They could even influence who makes critical maneuvers along the journey.

Preparations for 21st century space flights will see a movement away from the training by rote and the endless repetitions as seen in the past. Instead, there will be a more complete development of the educational aspects of the problem, based on better understanding of what will be necessary for spaceflight and what will constitute adequate preparation.

## FOLDABLE STRUCTURES FOR LUNAR BASES

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**ABSTRACT**--An early problem in establishing a lunar base will be the provision of enclosures for personnel, operational equipment, storage, mining, and agriculture, as well as open structures for the launching and landing of space vehicles. The purpose of this paper is to present a collection of foldable structures and foldable structural elements that appear to be well suited for use in remote locations, where placement and erection must be accomplished with minimum human effort and minimum energy. A structure made of "rigid" components properly hinged to fold compactly offers the user the advantage of assembling at the factory, transporting in a compact state, and erecting at the location of use.

The time and energy required to erect any structure are dependent on its size, mass, and the number of mechanical degrees of freedom residing in the structure as it arrives at the erection site. Conventional structures have thousands of degrees of freedom corresponding to the positioning of the many elements of which they are built. Even "prefabricated" structures have many degrees of freedom that must be dealt with in their erection.

Ideally a structure for use in a remote location should have one mechanical degree of freedom for erection. The more nearly this ideal can be approached, the greater will be the saving of time, energy and human effort at the erection site.

Folding means have been developed for a number of structural shapes including: rectangular parallelepiped, triangular prism, pyramidal enclosure, hip roof enclosure, gable roof enclosure, and geodesic dome. If the structural elements were true rigid bodies, the number of degrees of freedom for these shapes would be very small. But elastic deformation of the elements causes departure from the determinacy of rigid bodies with perfect hinges. For some foldable structures a small elastic deformation permits folding that would be impossible with true rigid bodies. Such elastic deformation can allow the hinge of one pair of elements to share, in its interstices, its axis with other pairs of elements.

The first five of the above shapes involve the reduction of a three dimensional structure to a two dimensional package with all elements remaining joined. The geodesic dome involves the reduction of a domed structure to a plane which can then, by disconnecting one hinged joint, be further folded to a "pie-shaped" package. After erection, these structures can be locked in place and reinforced if required.

The erection process can most conveniently be carried out by gas under pressure. Properly placed bladders can insure that the correct unfolding sequence is followed. Pressures required in a lunar setting would likely be small.

## INFORMATION MANAGEMENT FOR THE LUNAR BASE PROJECT

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The traditional NASA program evolves from interest groups within the aerospace industry and the administration. The life cycle of a program starts with a variety of concept studies which are usually termed pre-definition studies. These are followed by concept definition studies, known as Phase A studies. The subsequent phases are: Phase B, preliminary design; Phase C, design; and Phase D, development and operations. These phases are usually competed and may be performed by different contractors under NASA management. It is common for the NASA management team to undergo a major change for each phase. The continuity is primarily provided by documentation of the contractors work.

The commercial/business world has developed information management technology to a point where information systems are considered to be a crucial competitive tool. The development of these systems which are designed around the business enterprise, have an accompanying set of analysis and design techniques just as any aerospace system does. The underlying concept is that information is a resource that is the product of processes and data. The processes model the paths that handle and store information, while data is semantically modeled as objects about which information is collected.

An information architecture is developed, as is any other architecture, so as to provide direction, standards, and integration. The information architecture evolves out of enterprise strategic planning, specifically from a strategic information planning activity. The information architecture is further refined by subsequent logical analysis to form a data architecture which involves a global data model and leveling and distribution definitions to guide the physical development of the information systems. The core capability for the management and control of an enterprises information is a sophisticated data dictionary, which should comply with the proposed FIPS standard, Information Resource Dictionary System, (IRDS).

By considering a lunar base program as an enterprise, a high level information architecture is postulated. The processes are based on representative work performed for the Space Station Program, while the data models have evolved from local activities at JSC. The data models are: mission scenarios; transportation systems; and lunar surface infrastructure. Data definitions are currently being captured in a distributed PC data dictionary developed at JSC.

The introduction of an information architecture in the formative stages of a program provides at least two significant benefits. The first is the provision of concise definitions of the objects of concern to the enterprise. This facilitates discussions of the enterprise among many diverse groups with a minimum of misunderstanding through the use of the IRDS. This definition of the enterprise necessarily provides for a hierarchy and an appropriate granularity to enterprise detail as the program evolves with time. This feature is the basis for the second major benefit, that of the support of program integration and the carry-over of information in a consistent manner, from one program phase to the next. The program configuration management process becomes one of managing the configuration of the program, whether the data product is a document, a database, or a drawing.

The development of expertise in information management to support developing programs should be considered as an integral part of the new NASA strategic activity embodied in the Office of Explorations. Aside from bringing NASA into closer alignment with commercial business practice, the potential program lifecycle benefits are significant.



CONCEPTUAL ANALYSIS OF A LUNAR BASE TRANSPORTATION SYSTEM

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Central to the planning of a lunar base are transportation requirements necessary for the establishment and maintenance of that base. This work is part of a lunar base systems assessment effort at NASA Langley Research Center's Space Systems Division in conjunction with Johnson Space Center. Using a baseline lunar facility concept and timeline of developmental phases, weights for habitation and scientific modules (space station technology), power systems, life support systems, and thermal control systems have been generated. The transportation study manifests these weights, grouping various systems into cargo missions and interspersing manned flights for construction and base maintenance. A computer program that sizes the orbital transfer vehicles, lunar landers, lunar ascenders, and manned modules has been developed. This program uses an iterative technique to solve the rocket equation successively for each velocity correction in a mission. The  $\Delta V$ s reflect integrated trajectory values and include gravity losses. As the program computes fuel weights, it matches structural weights from General Dynamics' modular space-based OTV design. Variables in the study include the operational mode (i.e. expendable vs. reusable and single stage vs. two stage OTVs), cryogenic propulsion system specific impulse reflecting different levels of engine technology, and aerobraking vs. all-propulsive return to earth orbit. The use of lunar derived oxygen is also examined for its general impact. For each combination of factors, the low earth orbit (LEO) stack weights and earth-to-orbit (ETO) lift requirements are summarized by individual mission and totaled for the developmental phase. In addition to this discrete data, trends in the variation of study parameters are indicated.

It is immediately evident that construction and support of a lunar base will place a tremendous burden on any space transportation system. The initial developmental phase of the lunar base will require three to four million pounds total weight in LEO over the course of some 20 to 30 launches of a 150,000 pound heavy lift launch vehicle. Considering earth-to-moon-to-specific-base-location trajectory limitations, coupled with even the most optimistic ETO and LEO turnaround scenarios (not addressed in this report), this translates into several years of dedicated lunar missions. Aerobraking stands out as a critical if not enabling technology. Over the course of 16 lunar missions it can reduce LEO weights and corresponding ETO lift requirements on the order of 1.5 million pounds. Aerobraking is also critical in making a reusable OTV advantageous. It appears that using a two stage OTV yields no significant advantage in weight savings. In terms of operational logistics, then, a one-stage OTV makes the most sense. Utilizing lunar derived oxygen for lunar landing, ascent from the lunar surface, and return to earth orbit can reduce mission start weight from two to six times.

**A Single-Stage Vertical Takeoff and Landing Space Transport for Lunar Settlement Resupply.** Gary C. Hudson, President, Pacific American Launch Systems, Inc., 8 Admiralty Place, Redwood City, CA 94065.

Inexpensive and reliable means to transport cargo and people to and from lunar settlements will be required in the 21st Century if the exploitation of space is to occur in an economical and affordable fashion. We have considered a single-stage-to-orbit (SSTO) launch vehicle for use as a lunar transport. Since this design launches and lands vertically using rocket braking (VTOL), it is ideally suited for use both in earth surface to LEO missions as well as lunar landing missions. With orbital refueling (using either earth- or lunar-supplied liquid oxygen), the vehicle, which is named Phoenix, can carry a full 20,000 pound payload to orbit or the lunar surface.

This vehicle can be built using existing technology but its payload can be increased through the use of advanced propulsion and structures. One important technology which needs development is the use of water-cooled heat shields to reduce the turn-around time for the reusable vehicle, while at the same time permitting re-entry from either LEO or escape velocities simply by varying the water mass flow rate.

Cost per pound to the lunar surface is projected to be as low as \$200 per pound using earth-supplied propellants, and potentially half that employing lunar-supplied oxygen.

## THE ECLS SYSTEM FOR A LUNAR BASE: WHAT DRIVES ITS DESIGN

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Design specifications for a Lunar Base Environmental Control and Life Support (ECLS) System supporting a multiperson crew over a specific mission duration cannot be formulated without first having established some specific ground rules, design goals, and characteristics of the Lunar Base system. For the present study, the ground rules which, if imposed singularly or in multiples, overpower all other design drivers include: (1) an initial cost at launch or life cycle cost that dominate trade-offs of competing technologies, (2) an ECLS system design that must evolve from Space Station inheritance, and (3) a Lunar Base that must be self sufficient (a ground rule that probably cannot be totally achieved). After these ground rules are satisfied or eliminated as inappropriate, other design drivers become important. Drivers that most affect ECLS System and Subsystem selection include: (1) overall base composition and layout, (2) decision to man the base intermittently or continuously, (3) level of available power and type of power system, (4) atmosphere and water quality standards, and (5) approval or disapproval to use the Lunar environment (vacuum, surface heat, shadow, and subsurface cold) in the ECLS system design and operation. The next set of design drivers do not affect ECLS System and Subsystem selection, but they have a significant impact on initial launch and resupply weights, volumes, and costs. They include: (1) crew size, (2) resupply interval, (3) redundancy and fail operational/fail safe ground rules, (4) degree of water loop closure, (5) volume of pressurized surface structures (other than habitat), and (6) airlock operation scenarios.

It is obvious that early mission planning must include parallel consideration of all technical disciplines that contribute to the total base infrastructure. Ground rules derived unilaterally by mission planners may impose unnecessary penalties on the ECLS system design. Conversely, system designs developed unilaterally by the ECLS system engineer may limit the operational flexibility of the base or may violate some ground rule considered important by the scientific community.

## Making Concrete for Lunar Structures

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Most of the ingredients needed for making concrete are available in the moon's soil and rock. For this reason, concrete is a promising building material for lunar structures. A proposal is made regarding making methods of concrete on the moon.

A key feature of the proposal is the positive advantage taken of the moon's natural environment. Concrete can be made even at the moon's low gravity (1/6 G) and in a vacuum.

The main aspects of the proposal are as follows.

- (1) Water vaporize rapidly in a vacuum. But, ice won't vaporize in low temperature atmosphere like in a shade on the moon, because the saturated water vapor pressure in low temperature is very low. Therefore, powdered ice should be used for the mixing water of the concrete. This makes it possible to reduce the water-cement ratio and results in manufacture of a relatively strong concrete.
- (2) Pressure and vibration should be used in compacting the concrete. This method overcomes the difficulty of achieving a well-compacted concrete in the low-gravity conditions on the moon. The vacuum atmosphere should aid the compaction process, since air is not included in the concrete.
- (3) Microwave radiation or other such external energy will be used to melt the powdered ice in the compacted concrete and accelerate hydration. For the heating method, it is suitable to heat the whole concrete uniformly.
- (4) Amorphous material, which can be formed rather easily from materials found on the moon, is used to make reinforcing fiber and bars. Amorphous materials can also be used effectively in making tendon for prestressed concrete.

The above proposal for making concrete, including the processes from mixing to reinforcing, is a highly practicable approach to building lunar structures in a relatively short time. It should also form the basis for subsequent use of concrete techniques in space.

UNMANNED SURFACE DEVELOPMENT FOR MANNED LUNAR ACTIVITIES; T. Iwata, Tsukuba Space Center, National Space Development Agency of Japan, Sakura, Ibaraki, 305 Japan

Lunar surface platforms, penetrators and rovers have been proposed and investigated for unmanned lunar surface exploration. Unmanned development of lunar surface would follow those unmanned explorations before a manned lunar base operation. Teleoperated and semi-autonomous lunar robots are needed. Economical effects and future potential should be estimated.

The purpose of the unmanned lunar surface development is to prepare and demonstrate for a manned lunar base. Experimental operation of lunar manufacturing facilities will be of prime importance. Collecting materials for use in the initial phase of the manned lunar base should be included. Setting the foundation for the lunar base facility is also necessary. Experimental cultivation of plants and feeding of small animals could be planned. These unmanned activities will have clear target by setting a manned lunar base program.



**A COMPARISON OF WASTE PROCESSING METHODS FOR A CELSS:  
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The nitrogen recovery potential of various waste processing methods which could be employed in a Controlled Ecological Life Support System (CELSS) has been evaluated. The final analysis was used to develop a conceptual integrated system capable of meeting both the waste processing and nitrogen regenerating needs of a CELSS.

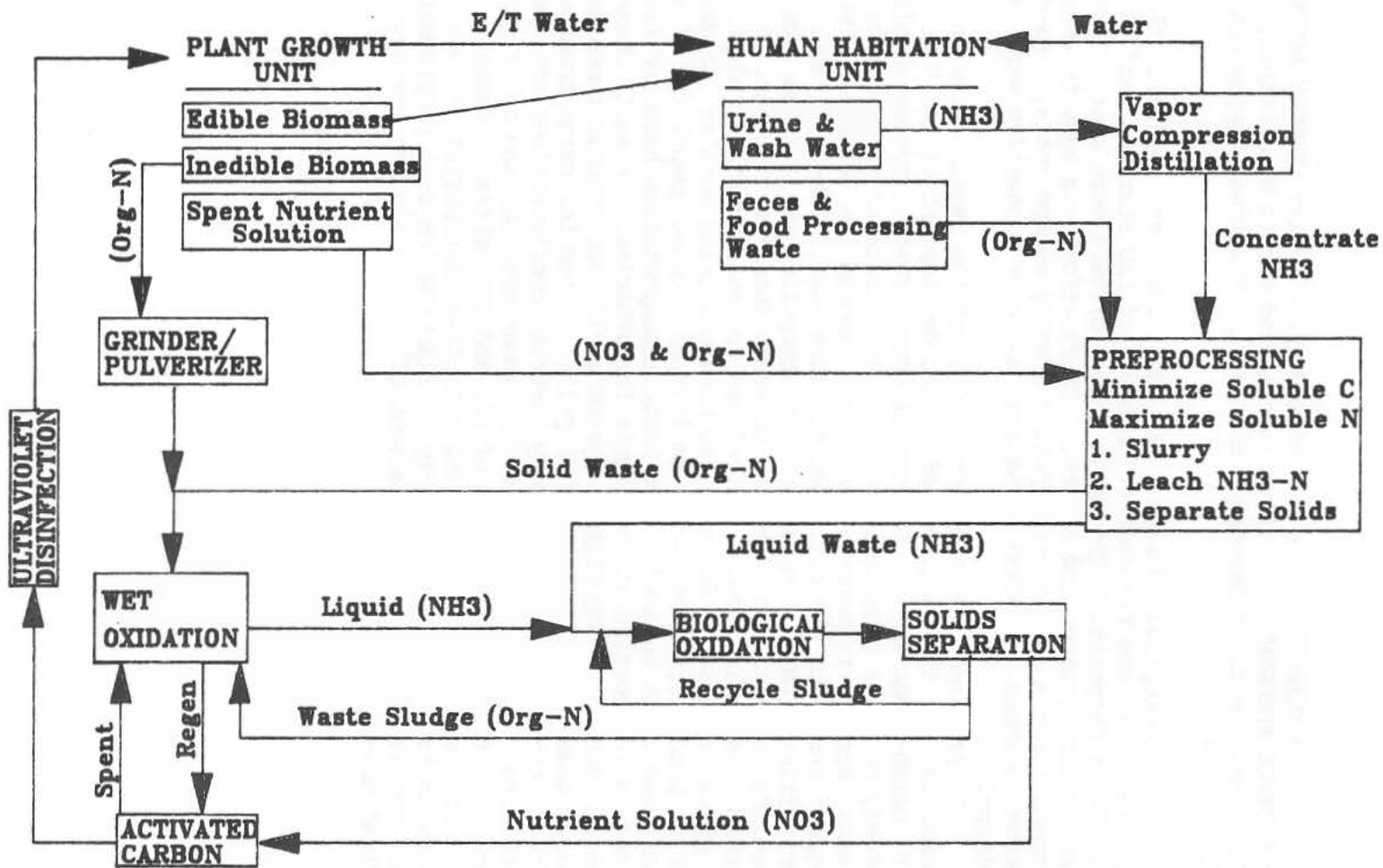
Waste processing can be achieved by three methods: physical/chemical, biological, or a hybrid of the two. An evaluation was performed to develop a system which would be best suited for meeting the waste processing needs of a CELSS. Physical/chemical options considered include: vapor compression distillation, wet oxidation, and supercritical oxidation. The biological waste processing technology most appropriate for a CELSS application is the activated sludge system.

One of the principal elements of interest to a CELSS, as well as its forms, is nitrogen. A summary of nitrogen recovery potential for each option listed above is presented below:

Option	Nitrogen Form, %				
	NH <sub>4</sub>	N <sub>2</sub>	N <sub>2</sub> O	Org-N	NO <sub>3</sub>
Vap Comp Distill	100	0	0	0	0
Wet Oxidation	58	13	0	12	6
Supercrit Oxid	0	68	32	0	0
Biological Oxid	2	0	0	11	87

Only those options capable of producing significant quantities of ammonium and/or nitrate ions are considered appropriate technology for meeting the nutrient regenerating needs of a CELSS. From the comparison presented above it becomes apparent that a hybrid system consisting of vapor compression distillation, wet oxidation, and biological oxidation may best be suited for meeting the waste processing and nitrogen regenerating needs of a CELSS. A schematic diagram of a proposed integrated system is attached. The treatment scheme is simplified to show the flow of nitrogen only.

## Nitrogen Recovery



A TRANSPORTATION INFRASTRUCTURE FOR 21st CENTURY ACTIVITIES OF THE U.S. SPACE PROGRAM, A. Steve Johnson and Marvin W. Luttges, University of Colorado, Dept. of Aerospace Engineering Sciences, Campus Box 429, Boulder, CO 80309

A conceptual design was undertaken to evaluate the operational interactions and transportation needs of LEO Station, and L1 Staging Node and Lunar Outposts. The major design drivers were cost, robust support of many space missions and safety. Every effort was made to conserve delta V expenditures and to avoid repeated gravity escape costs. Hardware systems, power systems, orbital dynamics and crew protection were given special attention.

A programmatic approach in lieu of the usual mission approach, is essential to the continued efficient development of the U.S. Space Program in earth-lunar space. An overall transportation system should not be based solely on lunar mission scenarios. An integrated optimization of all earth-lunar space transportation needs should be sought. Overall delta-V expenditures must be optimized for lunar-LEO, LEO-GEO, LEO-L1 and lunar-GEO activities. Large reductions in propelled mass can be achieved by not hauling specialized hardware to every lunar-earth site. Proper planning could result in reduced capital and operating costs by adapting a general purpose vehicle(s) for specific missions using modular hardware. Vehicle unit production costs would be lowered because quantities of simple modular hardware would be used. Two basic transportation hardware frames would be used as the configuration chassis for vehicles. A small chassis chemical-based manned transportation system would keep transit times small while a large chassis solar-electric propelled system for cargo transport would have lower operating costs. Many "hybrid" configurations are possible. Such vehicles will efficiently service lunar missions and an L1 staging site as well as the servicing needs of LEO and GEO orbits. Overall program costs will be reduced by establishing effective transportation nodes and flexible mission transportation hardware. Planning for such programmatic approaches is required now with the advent of LEO station and the development of a first generation OTV.

ASTRONOMY FROM A LUNAR BASE:  
STRUCTURAL AND OTHER ENGINEERING CONSIDERATIONS

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This paper reports on a continuing engineering investigation<sup>5, 6</sup> of three astronomical instruments that appear feasible for an early lunar base. The basic design considerations that are essential for scientific effectiveness are listed and evaluated for each. The three telescopes include a Very Low Frequency (VLF) array on the far side of the moon, the Moon-Earth Radio Interferometer (MERI), and an Optical/Infrared Interferometer. Our study includes telescope systems definition and specification, lunar soils and subsurface properties at potential sites, and the thermal, vacuum, radiation, gravity, micrometeoroid and other aspects of the lunar environment. The design constraints associated with emplacement and operation of each instrument on the lunar surface are examined. These constraints include dimensional stability in the thermal and vacuum environment, pointing accuracy and precision, and operational supportability. We assessed the new technology developments required in order to make it possible for these instruments to achieve their potential in the lunar environment. Some of the technologies considered are use of lunar materials (e.g., for shielding and construction), stiff, stable, light-weight structures and materials from earth (e.g., metal matrix composites), and the use of telepresence and robotics in construction, operation, and maintenance.

Our approach is to list the critical issues associated with each of the three telescope options (e.g., time - varying thermal strains in the structure and implications for telescope performance) and then for each issue point out the paths to its resolution. The lunar telescopes and their differences and similarities to terrestrial counterparts are discussed and developed based on visits to terrestrial telescopes and consultations with recognized experts. An engineering conceptual design is presented for a lunar telescope taking into account the basic design needs, design constraints, new technology options, and accepted paths to resolution of the critical engineering issues.

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ECONOMIC FOUNDATIONS OF PERMANENT PIONEER COMMUNITIES; Eric M. Jones, Earth and Space Science Division, Los Alamos National Laboratory, Los Alamos, NM 87545

Although pioneer settlements are often founded for political or ideological reasons distinct from short-term economic justifications, their survival and growth depend on economic factors. The settlers must be able to make a living, whether at subsistence, commercial farming, fishing, mining, manufacturing, trade, or in government service.

There appears to be two plausible means of supporting a lunar (or martian) settlement: 1) Mining/refining industries may provide only limited direct employment, but could provide (through lease/royalty payments) tax equivalents to support government-service jobs and public works, and could also be customers for local products which might otherwise have no markets. 2) Science bases and other government service industries could play much the same role as employer and customer. The history of settlement in Alaska and in Australia illustrates processes important when government service is a dominant industry.

Direct government participation in Alaskan development began in 1915 with construction of the Alaska Railroad. Built explicitly to promote development, the railroad was the sole source of support of Anchorage in the years before 1940. Anchorage was successfully run as a government town for its first five years. World War II and Cold War military construction along with other forms of government employment supported virtually all economic growth from 1940 until pipeline construction and oil royalties took over in the mid 1970s. High production costs, along with access to inexpensive consumer goods from outside Alaska, have thus far prevented most Alaskan products from competing in local markets.

Australia was settled in 1788 as a penal colony. Initially, food and supplies sent directly from England gave the colony time to develop its own production capabilities. Thereafter, a combination of high import prices, a work force with diverse skills, a small but important segment of the population intent on making its fortune in Australia, and a continued government presence led to the early emergence of a vigorous private-sector economy. Although there were virtually no external markets for Australian products during this period, government salaries along with commissariat purchases from private producers provided the equivalent of export earnings. After about 1820 the relative level of government participation in the economy declined, forcing some producers to explore export markets. Only after about 1830 did wool emerge as the supporting export.

Creation of a permanent lunar settlement is going to require an explicit commitment to such a venture and implementation of policies which will provide help in developing local production capabilities, permit transfer and/or sharing of supporting technologies and facilities, and provide to individuals and the community as a whole means of securing earnings sufficient to pay for necessary imports.

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**THE LUNAR HOOK LANDER - A LOW TECH, NON-PROPULSIVE  
LUNAR SURFACE ACCESS SYSTEM**

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An alternative to previously proposed non-propulsive lunar surface access systems is suggested. Not unlike an aircraft carrier landing, the system consists of a cable and hook extended from the landing vehicle intercepting a surface structure to perform the braking. Although surface construction capability will be required, the system can exploit simple "ski-lift" technology. Properly designed, the system is seen to perform well with very large margins of error. This is particularly attractive for routine, autonomous lunar base resupply and cargo delivery missions. Orbital transfer issues from low and high altitude lunar orbit are investigated. Key system orbital parameters include perilune altitude, eccentricity, true anomaly at intercept, max g-load, and intercept altitude. Optimizations are performed to minimize infrastructure size and required propulsive transfer burn. Two surface braking methods are proposed. The first implements a long cable coupled through a gear box to a frictional braking surface. The second attempts to exploit the orbital energy to generate mechanical and electrical energy for surface industrial processes.

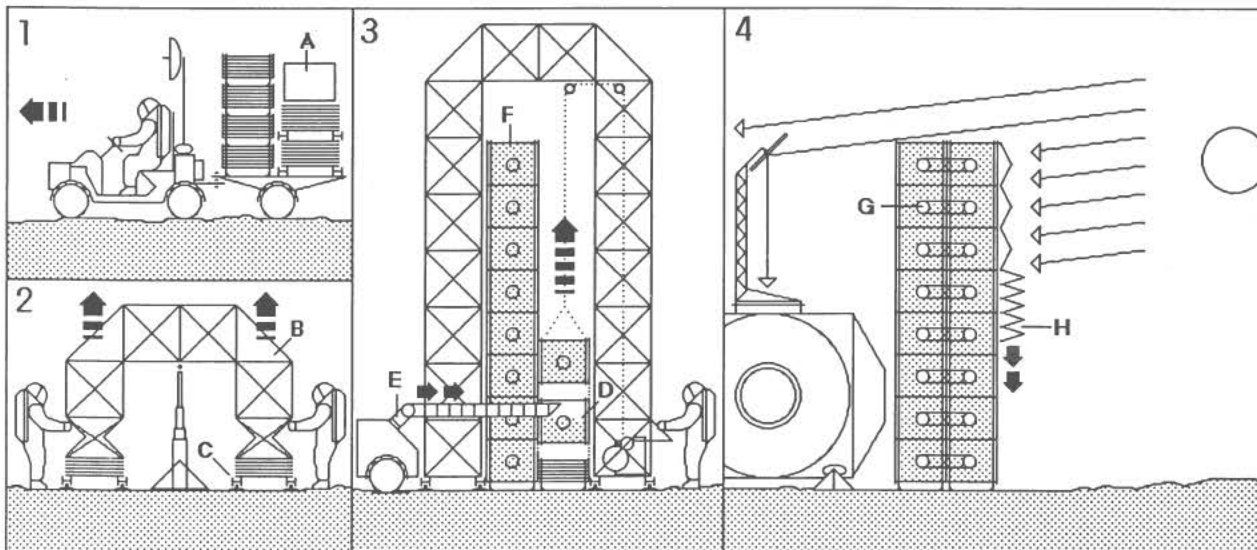
REGOLITH SHIELD WALL CONSTRUCTION FOR POLAR BASE LOCATIONS; J. Kaplicky and D. Nixon, Future Systems Consultants and J. Wernick, Ove Arup & Partners.

The choice of a polar location for a permanent Lunar Base (1) would require crew accommodation facilities to be protected from solar flare activity originating from very low sun angles. Assuming for reasons of economy and simplicity that the Lunar Base complex is located at surface level protected by an independent shielding system (2), free lunar regolith can be constructed as a reinforced vertical wall in-situ to surround the Lunar Base. Loose regolith would be deposited into a series of modular compartments which would be reinforced by lightweight structural stiffeners and constructed from the ground up using a simple moving gantry. The system would be tailored to the required profile for protection [approximately 2 meters thick by 7 meters high]; utilize a minimum of structural hardware ferried from Earth; and involve minimum construction crew effort and time on the Lunar surface.

Preliminary studies are focusing on the structural feasibility of an orthogonal grid of deployable membrane compartments with each compartment acting as a 'building block' containing approximately 1 cubic meter of bulk regolith. Compartments are strengthened and stiffened by contiguous reinforcement struts aligned vertically at each corner. The construction sequence is outlined in Figures 1 to 4. In Figure 1, the stowed hardware packages [A] are retrieved after landing and transported to the construction location. In Figure 2, a deployable gantry frame [B] is automatically erected on track [C] laid to the defined enclosure geometry [assumed to be circular]. The gantry frame construction would be based on technology derived from the Space Station beam structure development and already successfully tested in orbit (3). In Figure 3, shield wall sections are elevated in a bay-by-bay sequence with the gantry frame moving around the track until the enclosure is complete. Each bay comprises twin compartments which unfold vertically from a pallet at ground level. As each compartment is raised [D], it is filled with regolith [E], closed and secured, fitted with reinforcing struts and hoisted until all compartments are suspended from the gantry. They are then lowered and settle into compression with the struts interlocking 'tent-pole' style [F]. Regolith loads transfer vertically from compartment-to-compartment with the overall form of the wall contained and stabilized by the reinforcement struts. In Figure 4, compartment faces are strapped together for added structural safety using microfastener pads [G]. Finally, solar arrays are deployed down the outer face of the shield wall for power provision for the Lunar Base [H]. Heliostats are mounted above the accommodation modules to introduce controlled sunlight into the interior.

The studies demonstrate that **independent or 'stand-off' solar shielding systems eliminate the need for Lunar Base excavation and burial and provide an efficient and economical shielding method that does not impact systems configurations or operational considerations;** and that **terrestrial civil and structural engineering methodology and analysis techniques adjusted for Lunar environment conditions appear to be appropriate for Lunar Base engineering design development.**

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## POTENTIAL APPLICABILITY OF EUROPE'S PLANNED FUTURE IN-ORBIT INFRASTRUCTURE IN A LUNAR BASE SCENARIO

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The European Space Agency's Long-Term Plan 1987-2000 has the intention to (a) establish a comprehensive autonomous European capability in space, (b) strengthen a genuine partnership in the space field, (c) reinforce and expand the scientific programme, and (d) pursue vigorously activities in the fields of space applications and technology.

The four major programmes which constitute the first step of the future Europe space infrastructure are Columbus, Ariane 5, Hermes, and a data relay satellite (DRS). In addition, the Agency has started to study complementary elements such as the build-up of a European Space Station and an Ariane 5 based Logistics Vehicle.

This paper analyses the operational capabilities of the new European launcher system and of the new in-orbit facilities for the implementation and subsequent support of a Lunar Base Scenario. The scenario assumed consists of three steps:

- A small research base (3-5 crew members, 30-day missions, start implementation in 2005);
- An advanced research base able to produce and recycle parts of the consumables like oxygen, water, vegetable (10-12 crew members, 90 day-missions, start implementation in 2010);
- A pilot base for production from Moon material (15-20 crew members, start implementation in 2020).

The results show that Europe could considerably contribute to the implementation of the modular bases and to the subsequent logistics resupply. Main contributions could be:

- Ariane 5 for delivery of a power plant, a laboratory, a habitat and other modules in lunar orbit for transfer to the surface.
- Ariane 5 (which is man-rated in its basic design) for transportation of crew in a pressurized compartment and for resupply of consumables.
- Columbus technology for development of lunar base modules.
- EVA and advanced space robotics for assembly of the base and for Moon surface research.
- Advanced optical and rf technology derived from the Eureka-based inter-orbit communication experiment and the European DRS for space communications.
- The European Space Station for staging purposes in low Earth orbit and for the demonstration of equipment that can support long-duration manned missions

Finally, the paper discusses a number of programmatic issues which need to be clarified before Europe could consider its participation in such a large-scale and international effort.

## THE TRANSPORTATION DEPOT - AN ORBITING VEHICLE SUPPORT FACILITY

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In recent months the Space Station Office at NASA Langley has sponsored mission analysis studies to determine the impacts on the current space station design necessary to support the establishment of permanent lunar and Mars bases. One of the major results of these studies was the definition of requirements for assembly and refurbishment of the space vehicles needed for such missions. These studies have shown, among many other things, that the current space station design is capable of supporting vehicle processing, but that the necessary modifications would adversely impact both the astronomical viewing and the micro-gravity environments to the point where it would be highly desirable to separate such sensitive activities from the vehicle support facilities. This paper describes results of attempts to develop requirements and preliminary concepts for a Low Earth Orbit (LEO) facility, called a Transportation Depot, to support assembly and maintenance of vehicles for lunar and Mars missions.

The work described in this paper proceeded along two lines. First, a list of high level design requirements was established, and three preliminary Transportation Depot concepts were developed and evaluated against those requirements. Second, a quantitative analysis was performed which determined mass properties, orbital decay parameters, and flight mode attitudes for each concept. The following list shows a few of the design requirements from which the three depot concepts were developed.

1. Provide volume to accommodate vehicles and support equipment.
2. Provide Docking facilities to accommodate OMV and shuttle.
3. Provide a pressurized Command Center for controlling/watching EVA and robotic activities.
4. Provide capability for expansion.
5. Provide robotic and EVA access to vehicle and propellant tanks.
6. Provide for simple vehicle separation.
7. Provide micro-meteoroid/impact and thermal protection for vehicle, crew, and propellant.
8. Provide for containment of debris.

The three concepts which were developed were the Open Box, featuring truss sections arranged into a rectangular box which completely encloses the vehicle, the Prism, which encloses the vehicle within an equilateral triangular prism, and the Open Platform, which was derived somewhat from the dual keel space station configuration with the inner transverse boom removed and the keels rearranged to provide access to the vehicle.

The analysis described in this paper established the feasibility of the Transportation Depot concept and highlighted approaches for further refinement of designs. It was shown that high level system requirements such as those listed above, as well as performance requirements such as orbital parameters and flight attitude angles, can be met through a variety of designs. Finally, recommendations were made for expanding the analysis of this and other types of orbiting support facilities.



BONE LOSS AND HUMAN ADAPTATION TO LUNAR GRAVITY. T.S. Keller and A.M. Strauss, Mechanical & Materials Engineering, Vanderbilt University, Nashville, TN, 37235

Introduction: Long duration manned Lunar missions and space exploration are currently undergoing assessment. Potential human engineering problems involve low-gravity and artificial-gravity concepts, including "counter-measures" to reduce physiological degradation. This paper presents theoretical data on bone loss and skeletal adaptation to lunar life. Comparative data for other hypogravity environments is provided. The gravity-field question is addressed with the principal aim to define an optimal gravity environment that preserves physiological function and ensures survival.

Review and Theory: Manned space flights, lunar and mars missions and bases will take place in gravitational environments where the weight, defined as the force of terrestrial gravitation, experienced by the human or animal body will be reduced. A body of mass  $m$  on the earth (of mass  $M$  and radius  $R_0$ ) experiences a weight  $F_g = m(GM/R_0^2) = mg$ , where  $G$  is a universal constant and  $g$  is a constant equal to the acceleration due to the earth's force of gravity. On the moon, the weight or force of lunar gravitation will be  $1/6$  that of the earth. In space and earth-gravity simulated conditions of weightlessness (ie. hypoactivity) a significant loss of bone mineral and strength occurs in a relatively short amount of time. Physical exertion (ie. hyperactivity) and hypergravity, on the other hand, results in a significant increase in bone mineral and strength. During hyperactivity and hypoactivity the stress distribution in the bone and its metabolic requirements are altered, but the underlying mechanisms of these alterations or adaptations are not known and the consequences of bone loss have not been fully evaluated. It has been proposed that the adaptive response of bone is regulated by local mechanically derived stimuli and qualitative support for this has been provided. Recently, changes in human lumbar spine bone mineral content (BMC) in a group of world class power lifters were closely correlated to training intensity (weight lifted) [1]. This data can be expressed in such a way that  $BMC \propto (mg)^{1/8}$  where  $mg$  is the earth weight experienced over a one year time period. Assuming that bone adapts to reduced forces in a similar manner, then one can predict the changes in BMC during moon life ( $GM/R_0^2 = 1/6 g$ ) in terms of  $BMC \propto 0.799(mg)^{1/8}$  (eq. 1) where 0.799 represents the BMC fraction retained per year.

Discussion: Equation 1 predicts that, under normal activity conditions, a person will experience a 21.1 % reduction in lumbar spine BMC/year or an average weekly loss of 0.41 % in a lunar gravity-field. In terms of bone strength, this represents a reduction of 0.69 %/week [2]. Although the long term effects of fractional gravity on BMC and strength are unknown, losses ranging from -0.8 to -1.85 %/week during bed rest and -0.3 to -0.8 %/week during space flight have been reported, and hence the changes in BMC predicted by eq. 1 appear to be reasonable. Skeletal adaption to the lunar gravitational-field would require roughly 120 weeks for homeostasis (83.3 % strength reduction). The longest moon mission for a "safe" return to earth gravity would be about 96 weeks (66.6 % strength reduction). Additional factors, including homeostatic breakdown of other physiological systems in response to the diminishing mineral reserves and/or direct adverse effects of reduced gravity on normal cardiorespiratory, digestive, excretive, and immune system function, may reduce the safe survival period for lunar missions in the absence of musculoskeletal conditioning or artificial gravity.

- References:
1. Granhed, H et al. (1987) Spine 12:146-149.
  2. Hansson, TH et al. (1987) Spine 11:56-62.



## ACTIVITIES OF A SECOND GENERATION LUNAR BASE

Hugh M. Kelso and Brian Tillotson, Space Research Associates, Inc., 22907 - 15th Pl. NE, Redmond, Wa. 98053, with Joe Hopkins and Michael Thomas, members of Seattle Lunar Group.

This paper discusses requirements for the design of a permanent lunar base of 100 person size which may be able to expand to a base of about 500 person size.

Current plans for first lunar bases, as proposed by NASA and others, are for small groups of from 6 to 15 persons permanently occupying the base. NASA studies and the National Commission on Space Report plan on having a base on the moon by 2010, but we feel that activities in space will accelerate as commercial possibilities for exploiting space resources become more developed and as transportation costs are lowered. Projections by independent study groups show that a return to the moon could occur sooner than the NASA plan, given optimum conditions.

We think that there will probably be several small bases on the moon by the year 2005 (i.e., one Russian base, one ESA base, possibly a USA/NASA base, etc.). A larger "second generation" base with a population of 100 to 500 persons could begin to evolve on the moon starting around the year 2010. As activities on the moon increase, we anticipate economies of operation and construction costs for a base that will provide living and work areas for larger groups of people.

The initial lunar bases are almost wholly devoted to scientific experiments and exploration work. Second generation bases will begin to incorporate more commercial activity in that the development of lunar resources (e.g., mining and extraction operations) will best be done by private enterprise companies. At a population of 100 persons, we project some private activity, possibly just proprietary experimentation on processes. At the 500 person population, more extensive operations including export of mat'ls could occur.

Our design study has divided the possible activities of a second generation base into five major classifications: Construction, Scientific/Research, Business/Private Enterprise, Services required at the base, and Transportation/Logistics between the base and Earth. Some specific activities overlap these classifications but the goal of the study is to identify which activities will be the "drivers" for the base and to integrate the activities into a single design for such a base with emphasis on evolving from wholly government directed and financed activities to more privately funded commercial activities.

SERVICING AND MAINTAINING A LUNAR TRANSPORTATION  
SYSTEM IN LOW EARTH ORBIT (LEO)

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Space Station Architecture and Orbital Transfer Vehicle (OTV) studies have shown that space-basing OTVs in LEO offer potential economic benefits over ground-based systems. This paper describes a candidate space-based lunar transportation system and the requirements for accommodating it in LEO. The paper describes the candidate hangar/support equipment and the servicing and maintenance operations options, the comparison of the viable options, and the selection and definition of the most economical space-based transportation system turnaround operations in LEO at either a space station or free flying platform.

The first part of the paper will describe a candidate space-based lunar transportation system which has been used to perform the servicing and maintenance analyses.

Next the paper will present the requirements for servicing/maintaining a lunar transportation system in LEO. General Dynamics has used our experience in processing the ground-based Shuttle/Centaur cryogenic upper stage to identify the functions, operational tasks, and support equipment needed to operate a space-based cryogenic system. The space operations to be performed cover the system assembly on orbit, launching, servicing/maintenance, payload integration, and retrieval.

Candidate accommodation servicing concepts will be presented including variations ranging from EVA only to a fully pressurized hangar with shirtsleeve servicing. Alternative methods for performing the turnaround operations such as EVA only, EVA with teleoperations, teleoperations only, or teleoperations with automatic disconnect will be investigated.

A comparison of the accommodation servicing concepts will be shown and the rationale for selecting an unpressurized maintenance facility/propellant depot will be presented. A comparison of the alternative turnaround operations options will be presented and the rationale for selecting the approach for using teleoperations for most tasks except changing out the thermal protection system on the aerobrake using EVA will be explained.

The selected servicing/maintenance facility will be defined including the interfaces with the lunar transportation system and the LEO facility and the support requirements needed from the LEO facility. The timelines to perform the turnaround operations as well as the manpower requirements and skills will be presented. Thus a total scenario for basing a lunar transportation system in LEO will be presented to perform the required missions starting in the late 1990's.

The paper will also describe how the servicing and maintenance approach used in LEO could be extrapolated to a facility in lunar orbit. In addition, the technologies advancements required to attain the projected space-based operational capability will be described.

REGOLITH AND ROCKS FOR LUNAR STRUCTURES AND SHIELDING;  
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Utilizing lunar resources as primary construction and shielding materials can be a major factor in initial development and future self-sufficiency of lunar bases. Unprocessed or minimally treated lunar materials can be used to generate structures, similar to those in terrestrial harsh desert regions, which have created a suitable human environment. Many ingenious techniques have been invented, perfected, time-tested, and repeatedly used in the last four millenia, demonstrating their validity. (1) Utilization of such techniques can contribute to several major results:

- a) In-situ generation of structures.
- b) Thermal/radiation/impact shielding (2) of structures attained through mass-and-form parameters.
- c) Economical and self-sufficient construction programs using low-gravity, medium-span natural structures, with on-site materials.
- d) Human interaction with natural environment, developing physiological compatibility and flexibility of response to challenges of everyday existence. (3)
- e) Inclusion of Native American and Third World contributions in the space program, thus adding to global unity and revitalizing traditional earth-building technology by integrating high technology/low technology.

The proposed paper will demonstrate, through description and graphics:

- 1) The innovated and perfected traditional systems of single and double curvature compression shell structures—arches, vaults, domes, apses—and their use in construction and shielding of lunar base structures. It will also present the practiced systems of shell building techniques in corbelling, dry-packing, leaning arches, pendentives and squinches.
- 2) Use of unprocessed lunar rocks and meteorites with higher fracture strength in an anhydrous environment (4) to generate structures.
- 3) Lunaradobe production and construction. Utilizing unprocessed regolith as the basic material and Earth Structure (adobe, rammed earth, etc.) techniques as the construction system to generate lunar base structures.
- 4) Describe in more detail previously proposed lunar construction technology of "Magma, Ceramic, and Fused Adobe Structures Generated In-situ" (Lunar Bases Conference, 1985)

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## LUNAR SUB-SURFACE ARCHITECTURE ENHANCED BY ARTIFICIAL BIOSPHERE CONCEPTS

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Lunar sub-surface architecture can be greatly enhanced by applying design concepts of artificial biosphere technology. These applied designs will not only make the structures more habitable in the short term but will ultimately provide the self-sufficiency factors necessary for the mature lunar settlement. The integration of artificial biospheric technology and sub-selene architecture creates a habitat offering a balanced lifestyle while maximizing lunar resources.

A first stage lunar base can be created using a tunneling device that produces an underground network of habitats, work spaces and passage ways. The resulting interior walls of the tunneled chambers are hardened silica to which inflatable membranes can be attached and deployed creating the desired environment. These habitats will be essentially isolated from the lunar surface environment by a closed structure composed of components derived from the lunar surface itself. Like a biosphere, these lunar base structures will strive to be a stable, complex, evolving system containing life, essentially closed to material input or output, and open to energy and information exchanges. To be cost-effective, the lunar bases will need be total systems that provide not only shelter but also a stimulus to work and learn.

There are many artificial biosphere design concepts which can enhance the sub-surface architecture. Dropping the floorline can create a gradient that will drive interior convection currents. An outgassing lung device will eliminate leaks in the structural seal. The sealing and glazing techniques used in artificial biospheres are important because without them a biosphere-like structure would be useless for space colonization. Other crossover technologies from artificial biospheres to lunar habitats include; energy devices, air and water filter systems, food production and waste management to name a few.

Artificial biosphere technologies can enhance the sub-surface lunar habitats. These technologies can be integrated in even the first stage lunar base and evolve with the structure as a total system creating a self-sufficient mature lunar settlement.



## CREATING A FOUNDATION FOR A SYNERGISTIC APPROACH TO PROGRAM MANAGEMENT

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Previous large, multi-center NASA programs have been accomplished by dividing the program into elements (eg, command module, Saturn V booster, Orbiter) which were designed, developed, and integrated by a prime contractor under the management of a single NASA center. While this method minimized the managerial complexity of a given program, it has created an organizational structure within the Agency which makes it difficult for new NASA programs to effectively use hardware and resources developed for previous programs. Therefore, each new NASA program must essentially "start from scratch." In order to accelerate the movement of humans into space within reasonable budgetary constraints, NASA must develop an organizational structure which will allow the Agency to efficiently use all of the resources it has available for the development of any program the Nation decides to undertake.

This work considers the entire set of tasks involved in the successful development of any program. Areas which hold the greatest promise of accelerating programmatic development and/or increasing the efficiency of the use of available resources by being dealt with in a centralized manner rather than being handled by each program individually are identified. Using this information, an agency organizational structure which will allow NASA to promote inter-program synergisms is developed.

In order for NASA to efficiently manage its programs in a manner which will allow programs to benefit from one another and thereby accelerate the movement of humans into space, NASA must:

- develop an organizational structure which will allow potential inter-program synergisms to be identified and promoted; key features of the organizational structure recommended in this paper include:
  - the establishment of a single office which performs the mission analysis and system engineering functions across all NASA programs and, therefore, replaces the performance of these functions as part of each individual program
  - the establishment of technical discipline agents to perform subsystem management on an Agency-wide basis as opposed to having each NASA center provide its own subsystem managers to support the development of those elements for which the center is responsible
- begin to develop the requirements for a program in a manner which will promote overall space program goals rather than achieving only the goals which apply to the program for which the requirements are being developed; and
- consider organizing the Agency around the functions required to support NASA's goals and objectives rather than around geographic locations

If we are serious about moving toward the permanent presence and expansion of humans into space, NASA must organize itself to be able to treat the space program as a program rather than as a collection of individual initiatives.



**LIFE SUPPORT TECHNOLOGIES:  
FROM SPACE STATION TO LUNAR BASES**

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Early development of a Lunar Base life support system will be critical to preclude problems associated with insufficient lead time. Currently under development, the Space Station Environmental Control and Life Support System (ECLSS) program will produce the first partially recycling life support system. This system, along with Space Station "fall-out" technology, will provide a basis for the life support system to be used on the moon. Also, Space Station ECLSS development facilities may be shared as a cost and scheduling enhancement for the Lunar Base advanced technology development. For a smooth transition from Space Station to Lunar Bases, the planning must begin now.

This paper addresses that effort in three phases; First, the technology requirements for lunar life support are defined. This phase will make extensive use of published sources. Second, the Space Station ECLSS will be outlined and subsystem technologies defined. Finally, key technologies deemed appropriate for a Lunar Base will be classified according to development status: (a) part of the Space Station program, (b) not part of the Space Station program but being developed under separate funding, and (c) not part of the Space Station and in need of development. Parts (a) and (b) above will be further classified according to sufficiency of effort relative to that required for timely development.

The development of a system level computer program to evaluate how developing technologies will interact, and the use of that program in competitive analysis of life support scenarios for future manned missions is also described.

THE INFLUENCE OF LUNAR PROPELLANT PRODUCTION ON THE COST-EFFECTIVENESS  
OF CIS-LUNAR SPACE TRANSPORTATION SYSTEMS

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It is well known that propellants produced at the points of destination such as the Moon or Mars, will help the economy of space transportation particularly if round trips of a crew are involved. The construction and operation of a lunar base shortly after the turn of the century is one of the space programs under serious consideration at the present time. Space transportation is one of the major cost drivers. With present technology the specific transportation costs of one way cargo flights are approx. 7 000 (1985) \$/kg at (cumulative) 100 000 tons to the lunar surface, if expendable launchers would be employed. A fully reusable space transportation system using lunar oxygen and earth produced liquid hydrogen, would reduce the specific transportation costs by one order of magnitude to 700 \$/kg at the same payload volume. - Another case of primary interest is the delivery of construction material and consumables from the lunar surface to the assembly site of space solar power plants in geostationary orbit. If such a system is technically and economically feasible, a cumulative payload of about 1 million tons would be required, probably even more. At this level a space freighter system could deliver this material from Earth for about 330 (1985) \$/kg to GEO. A lunar space transportation system using lunar oxygen and a fuel mixture of 50 % AL and 50 % liquid hydrogen (which has to come from Earth) could reduce the specific transportation costs to less than half, approximately 150 \$/kg. If only lunar oxygen would be available, these costs would come down to 200 \$/kg. This analysis indicates a sizable reduction of the transportation burden on this type of missions.

It should not be overlooked, however, that there are several uncertainties in such calculations. It is quite difficult at this point in time to calculate the cost of lunar produced oxygen and/or aluminum. These will be functions of production rate and life cycle length. In quoting any costs of this nature it is very important to state the cumulative transportation volume, since this is a very sensitive parameter. Nevertheless, cost models must be developed now to understand fully the interdependencies of a large number of parameters and to provide the best possible data for planning purposes. Without such data mission modes and vehicle designs or sizes cannot be selected intelligently.

The information presented in this paper must be considered to be preliminary, since this analysis was based on data from other models which are in the process of being improved.

LUNAR RESOURCE RECOVERY - A DEFINITION OF REQUIREMENTS;  
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The desire to locate, mine, and process lunar ores for oxygen, hydrogen, and strategic minerals is an established goal of lunar basing. A variety of scenarios for the development and utilization of a lunar base have been proposed. Regardless of the specific scenario, the need to use lunar resources to satisfy mission objectives is explicit; the need to do so in a safe, expedient, and energy-sensible fashion is also implicit in the various alternatives under consideration.

It is first necessary to identify concentrated sources of the desired ores, such as ilmenite or chromite. Initial reconnaissance by space based multi-spectral scanning may provide effective, large scale, exploration coverage. Ground based geophysical techniques, such as radar and resistivity surveys, complement space based remote sensing at identified targets. Lunar resistivity surveying offers considerable promise over terrestrial application in that the absence of pore fluids greatly enhances resistivity contrasts and thereby accentuates resolution. Radar methods offer the possibility of providing rapid and continuous, vehicle mounted, probing of the subsurface to relatively modest depths. Resolution and penetration are functions of both probing frequency and contrast in dielectric contacts between host and potential ore. Primary goals of all surface borne geophysics techniques are to provide preliminary location of ores and potential resource recovery sites without requiring direct crustal or regolith penetration by drilling. The adverse influence of hard vacuum on lunar drilling efficiency and feasibility highlights the desire for effective remote geophysical sensing.

Exploration and orebody definition are on-going processes in terrestrial mining operations; the same need will exist in a lunar mining operation. Due to the nature of the environment and the likely presence of robotic equipment, a need for in-situ characterization through automated remote sensing can be envisioned.

The mining systems and equipment ultimately used to mine lunar ores will differ from their terrestrial counterparts due to environmental and material differences. Transportation constraints will also significantly impact the available systems and equipment options, at least in the early years of base development. While many of these differences will increase the difficulty of exploiting lunar ores, some may make it easier. Terrestrial surface mining systems, for example, are heavily influenced by environmental requirements for the handling of spoil materials, but this may not be an issue in a lunar operation, thereby simplifying both the mining system and the associated equipment.

The necessity of minimizing moving parts, due to anticipated lubrication problems, has been identified, and points towards the need for non-traditional means of rock fragmentation. Of the possible alternatives, the proposed in situ rock melting concept appears to hold promise. However, the full-scale feasibility of the concept, as applied to tunnelling appears questionable, particularly with regard to its enormous energy requirements.

The potential feasibility of explosive usage in a hard vacuum has been determined, and despite the obvious problems of blasting in a low gravity environment, may offer promise.

It appears that feasible surface and underground mining systems can be formulated around blasting. The proposed in situ melting concept would be used to create small diameter holes to accept explosives; subsequent to blasting, mucking and hauling could be done using robotic vehicles. On-going research suggests that even the drilling and blasting unit operations can be executed by robotic machines.

Another aspect which deserves additional attention is the use of the underground openings for habitation, storage, and emplacement of nuclear reactors. The natural link between the mining operation and creation of useful space is not without precedent, and must be considered in the formulation of candidate extraction methodologies. This could also complement usage of lava tubes.

TWO LARGE-SCALE LUNAR GEOCHEMICAL PROBLEMS; REASONS FOR DETAILED SAMPLING AT A LUNAR BASE SITE; R. L. Korotev and L. A. Haskin, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130

Samples of secondary igneous "melt rock" have been found at all lunar highlands sites. Several hand-specimen sized samples were collected (e.g., samples 14310, portions of 15445, 65015), but most melt rocks analyzed are clasts from complex breccias or fragments from soils. At each site, these fall into a few distinct compositional groups. Melt rocks appear to be fragments from large, homogeneous melt sheets that formed pools in the bottoms of large impact craters. Many melt rocks are noritic in composition and contain a higher proportion of iron- and magnesium-bearing minerals relative to plagioclase than average lunar highlands surface crust. Particular melt rock compositions may represent specific large craters or major basins such as Serenatatis or Imbrium. If so, fragments of melt rock can serve as indicators of the origin of the ejecta in local regolith. The composition of 14310 from Fra Mauro is nearly indistinguishable from that of 65015 from Descartes except for trace siderophile elements, which indicate that each rock or melt sheet was made by a different impacting projectile. Are these samples from a common Imbrium melt sheet, or are they fragments from melt sheets that just happen to have very similar compositions but were produced in smaller craters a long distance apart? Why are many melt rocks noritic in composition? Are they partial melts, and therefore similar? Do they represent the mean composition of the highlands crust at a few kilometers depth, indicating that the crust is noritic there, in contradiction of the notion of a thick anorthositic crust? Do they come from beneath a thick anorthositic crust, and therefore are produced only by the largest cratering events? We do not have enough representative samples to know. Detailed sampling over a 50 - 100 km<sup>2</sup> area and high-grading could provide enough large samples of melt rock free from adhering matrix to indicate the scale of occurrence of these important indicator rocks.

We lack accurate knowledge of the types and proportions of highlands igneous rocks that is key to understanding how the Moon's earliest crust formed and, thus, how its interior became chemically differentiated. Consider the Apennine Mts., a major formation made of material excavated from the Imbrium Basin, material that represents thousands of km<sup>2</sup> of ancient highlands crust. We have identified the Apennine Front highlands component chemically through the compositional variations it causes in Apollo 15 soils, which are mixtures of mare and highlands rocks. However, the Apennine Front component itself is a soil, and it is a soil that is not a mixture of the igneous rocks obtained by the Apollo 15 mission that we have been able to identify. Surviving rock fragments may be rare on the Apennine Front, but they probably exist and extensive sampling of a small area on the Apennine Front would probably find them. We might have to sieve much soil to find them, and try more than one sampling station to find them. A search could be carried out from a lunar base.

These specific examples are intended to illustrate how detailed sampling in the vicinity of any lunar base will have application to large-scale lunar problems.



TRAJECTORY DETERMINATION AND CHARACTERIZATION  
OF CISLUNAR LOW-THRUST SPACECRAFT

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This paper describes the characterization of a low-thrust spacecraft traveling between nuclear-safe Earth orbit (NSEO) and low lunar orbit (LLO) and the trajectory determination methodology used to generate the orbital transfer requirements for the vehicle. The spacecraft is a cislunar orbital transfer vehicle (OTV) using nuclear electric propulsion to carry payloads to LLO in support of a lunar base. The vehicle will depart from NSEO of 800 km upon receiving a payload dispatched from the space station. After a spiral Earth escape and coast, the vehicle will spiral into LLO where the payload will be removed for transfer to the lunar surface. The vehicle then returns from LLO to NSEO. Aerobraking is not an option for Earth orbit capture due to the spacecraft's nuclear power system.

Reference trajectories for a guidance and thrusting control algorithm are developed in the classical two-body systems for the Earth and Moon capture spirals. The central body's oblateness is the only perturbation considered during the spiral trajectory development. The velocity components in the radial and tangential directions are formulated from these trajectories as functions of radial distance from the Earth or Moon. The complete cislunar trajectory is generated in a three-body system using a thrusting control algorithm to drive the vehicle to the reference flight condition.

A low-thrust vehicle is developed using proposed designs and current technology to characterize the vehicle components and systems. All major systems, such as propulsion system, power system, and support structure, are parameterized to allow for scaling of the vehicle size. An initial vehicle design is used to generate the reference trajectories. The initial vehicle characteristics are used as first estimates for the propellant mass and payload capability of a cislunar transfer vehicle. The final vehicle performance characteristics are determined after a complete LEO-LLO-LEO trajectory is generated. These characteristics include: trip time, thrusting history, propellant mass, and outbound and return payload capabilities, as well as other operational considerations.

ADVANCED COMMUNICATIONS, ROBOTIC VISION, AND TRACKING SYSTEMS  
FOR LUNAR BASES AND SPACE OPERATIONS

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Technology advancements in the areas of tracking, communications, and robotic vision sensors being pursued within NASA, as applicable to Lunar Bases and associated space operations, are presented. Systems concepts for efficient and reliable communications, tracking, and robotic vision are discussed. Communications systems for multiple access, broadband, high data rate, and efficient operations are given. Optical-, laser-, and millimeter wave-based implementations of both communications and tracking systems are discussed. The incorporation of NASA's anticipated space communications and tracking assets, which includes Tracking and Data Relay Satellite Systems, Shuttle(s), Space Station, Global Positioning System, Advanced Communications Satellites, Space Communications Center(s), and Orbital Transfer Vehicles, in the overall Lunar Base scenario is presented. Current NASA efforts at Ka- and W-bands are summarized. The use of smart television, laser, and microwave sensors for robotics operations is discussed. Optical processing for autonomous rendezvous and docking operations is presented. The fusion of systems ranging from microwave to optical wavelengths and high-level data processing techniques for remote control, station keeping, tracking, inspection, repair, and assembly is detailed.

# INTERDEPENDANCE OF THE MOON, PHOBOS AND DEIMOS

David L. Kuck, Geological & Mining Consultant.

The Moon is devoid of essential biogenic resources such as water, hydrocarbons and nitrogen. Oxygen can be obtained by reduction of oxides, but any development on the Moon must have a ready supply of the other vital volatile resources, hydrogen, carbon and nitrogen. Being volatile, these gasses and many of their compounds are easily lost to the vacuum of space. Bringing them from the Earth is prohibitively expensive so extraterrestrial sources of these materials must be found.

If Phobos and Deimos are indeed carbonaceous chondritic satellites, they are ideal early targets for extraterrestrial exploitation. They may contain biogenic resources such as water, hydrocarbons and nitrogen, all of which are absent on the Moon. The water and soluble salts can form the basis of wet chemistry.

Carbonaceous chondrites contain hydrated and water soluble metal salts such as epsomite ( $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ ) and gypsum ( $\text{CaWO}_4 \cdot 5\text{H}_2\text{O}$ ) along with hydrated clay minerals, elemental sulfur and arsenic. The first step in treating carbonaceous chondrites is to wash them thoroughly with water, acid and/or alkaline solutions to recover soluble salts. Then retort the washed chondrite to recover the wash and chondritic water. Raising the temperature of the retort further will drive off elemental sulfur and arsenic. The retorted chondrite can then be comminuted and treated by physical processes to separate the constituent minerals. The mineral concentrates may then be treated by various pyro or wet chemical processes to obtain other desired products.

The water soluble magnesium salts recovered can be treated to recover refractory magnesite and magnesium metal. Magnesium metal, exposed to space vacuum, must be coated with aluminum to prevent sublimation due to magnesium's high vapor pressure.

CI chondrites contain magnetite  $\text{Fe}_3\text{O}_4$ , an easily reduced iron oxide. Chondrites contain iron, nickel and cobalt silicates, along with any magnetite, which can be reduced to metal by hydrocarbon reducing agents. The hydrocarbons are finely divided and dispersed throughout the chondrites, which will allow direct reduction of iron, nickel and cobalt upon heating, along with production of  $\text{CO}$ ,  $\text{CO}_2$  and  $\text{H}_2\text{O}$ .

Xenoliths, which are present in many meteorites, may provide a variety of other meteorite compositions, both chondritic and achondritic which may be treated with the materials derived from the carbonaceous chondrite.

The delta-V for a round trip to Phobos or Deimos from LEO is less than a round trip to the surface of the Moon, although the travel time to Mars is longer, more than two years. The deep atmosphere of Mars can be used for atmospheric braking for achieving orbital capture by Mars. The extremely small size of Phobos and Deimos in relation to the Moon, means that low thrust devices can be used for a landing and departure.

Another benefit from a base on Phobos and/or Deimos is that it can provide a base for detail mapping of Mars.

Phobos and Diemos should be explored and developed before bases are developed on the Moon. Phobos and Diemos may have the same problem encountered on the Moon, that is the loss of volatiles due to collision heating, since they are deep in the gravity well of Mars. Fresh unheated carbonaceous chondritic rock is needed with all or most of its volatiles. If all or most of the volatiles are lost, then earth approaching carbonaceous chondritic asteroids should be considered as primary sources of biogenic materials for support of Lunar development.

**FUSION ENERGY FROM THE MOON FOR THE 21ST CENTURY;** G.L. Kulcinski, I.N. Sviatoslavsky, J.F. Santarius and L.J. Wittenberg, Fusion Technology Institute, Dept. of Nuclear Engineering & Engineering Physics, University of Wisconsin-Madison, 1500 Johnson Drive, Madison, WI 53706-1687

The demand for energy in the 21st century will be one of the most critical problems facing the inhabitants of the earth as well as those living in space. It is highly likely that the world will transcend from a fossil fuelled economy to one based on nuclear energy somewhere in the middle of the 21st century. The only question now is will the nuclear energy be derived from fission of fusion fuels? The object of this paper will be to examine the use of one specific and very attractive fusion fuel (Helium-3) in the context of how it could affect life on earth in the 21st century and how the use of this fuel could benefit the commercial development of the moon.

The benefits of using a fuel cycle which greatly reduces the fraction of energy released in neutrons have been known for over a decade and discussed in several recent review articles.<sup>(1-3)</sup> The use of this cycle for space power and propulsion has also been described.<sup>(4,5)</sup> One of the key questions arising from all of these studies has been how difficult it is to obtain the He-3 from the lunar surface? Analyses given in this paper will show that the energy payback, i.e., the energy released in burning a kg of He-3 with 0.67 kg of D<sub>2</sub> divided by the energy required to transport the men and equipment to the moon plus the energy required to operate the equipment, is 250-350.

Another major question that is addressed in this paper is what will the operators of the mining operation do with the lunar volatiles evolved during the procurement of the fuel? There will be some 500 tonnes of N<sub>2</sub>, over 5000 tonnes of gaseous carbon compounds, and 6100 tonnes of H<sub>2</sub> evolved for every tonne of He-3 extracted. The availability of these gases on the moon will be of great benefit to lunar colonies for life support and atmosphere control. It is estimated that the 6100 tonnes of H<sub>2</sub> (in the form of water) alone could provide for the needs of over 40,000 people living on the lunar surface for 1 year. The 500 tonnes of nitrogen will provide for the food and atmosphere needs of 1400 people.

Finally, the rate at which He-3 could be needed on the earth is analyzed. It is found that if the first commercial D-He<sup>3</sup> power plant is built in 2015, then by 2025 approximately 1 tonne of He-3 per year is required and by the year 2035, 10 tonnes per year would be needed.

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## A PLANT IDEAL FOR A LIFE SUPPORT SYSTEM ON THE MOON

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For extended life in space, there is a need to develop a life support system that would meet human requirements of food, atmospheric control and waste management. Several experiments on the adaptability of animals and plants in space were conducted by both US and USSR space shuttles. We propose to study a unique plant, the winged bean (*Phosphocarpus tetragonolobus* (L), D.C., which was brought to prominence by the U.S. National Academy of Sciences (1979), in a closed environmental system to be built on the surface of the moon.

All parts of the plant are edible. The leaves of the plant are cooked and eaten like spinach. Succulent shoots resemble asparagus; flowers (steamed, or fried) serve as sweet garnish like mushrooms; the pods when tender, can be eaten raw, steamed, boiled, stir-fried or pickled. Tender seeds in pods or mature dry seeds are a very good source of complete protein, slightly superior to soya bean. Above all, the roots of this plant grow into tubers in some species, which can be used like potatoes. The absence of any waste products makes winged bean the ideal choice for studies in space. It is proposed to (1) identify the ideal conditions of growth in artificial ecosystems, (2) determine the nutrient value of the seeds at various stages of development in the pods and at various stages of germination, (3) grow winged bean as hanging plants for which it should be ideal since it is a climber. Growing down will simulate gravity nullification by shoot inversion causing the release of apical dominance which should result in fast growth and decreased ethylene production (reduces waste production). Clonal multiplication from endosperm or embryo by tissue culture and acceleration of growth by induced flowering to decrease the cycle of growing and cropping will also be studied. Winged had been grown in the eastern shore campus of the University with partial success. Preliminary studies on the germination characteristics of the seeds and generation of callus cultures from endosperm have been successfully completed. The lunar base offers a unique opportunity for this study.



ROLE OF FREE RADICAL SPECIES OF OXYGEN IN SPACE  
RADIATION DAMAGE AND THE USE OF ANTIOXIDANTS FOR  
RADIOPROTECTION, A POSSIBLE STUDY FOR THE LUNAR BASE

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Exposure to different kinds of radiation is a factor to be seriously considered in any long-term manned experiments in space. Electrons, protons, bremsstrahlung, solar flares (protons,  $\alpha$ -particles, high energy and charge particles, known as HZEs), galactic cosmic radiation (protons and HZEs) and man-made radiations are important among them. Since the quality of these radiations are different, the effects of any one type of radiation may potentiate the effect of another type of radiation. This indicates the urgency and the significance of understanding mechanisms of damage by these radiations and devising means of protection. Most of the current knowledge on protection is based on data from ionizing radiation (such as gamma) where indirect damage due to radiolysis of cellular water predominates. Free radical species of oxygen are known to be involved in these processes. Using red cell membrane systems we have shown that superoxide, hydrogen peroxide and hydroxyl radicals are involved in the radiation-induced lipid peroxidation. The membranes can be protected by scavengers of these radicals- superoxide dismutase, catalase, and benzoate. In other studies using animals, we have shown that chemical radioprotectors can modulate the activity of glutathione peroxidase, another antioxidant enzyme. Thus these enzymes seem to play an important role in radiation damage. These studies are done with very high doses of radiations. Studies will be done with low levels of radiations and also with mixed qualities of radiations to determine the role of antioxidant enzymes in conditions similar to that existing in space. This may help in devising methods to induce these enzymes or administer other scavengers of free radical species of oxygen like vitamin E or selenium which may protect from space radiation effects. The lunar base will provide an ideal environment for these essential studies.

MOON PARK  
A RESEARCH AND EDUCATIONAL FACILITY

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The concept of Moon Park was put forward at Pacific ISY Conference, Hawaii, August 19-21, 1987. The Moon Park is a facility complex to be constructed under international collaboration.

The core facility of Moon Park is a crew training center associated with CELSS ( Closed Ecological Life Support System). The center is to simulate the human settlement in the frontier bases on the moon as well as other planets. Such a frontier base, where the crew of less than 30 members are isolated, is vulnerable to psychological disturbances among crew and CELSS failures, and likely to result in catastrophe. The stability and reliability of crew relations and CELSS, therefore, are the study subjects not only prior to the facility construction but also during the crew training. Some of the crew may be scientists of these research fields.

The design philosophy of CELSS is

- Early construction using off-the-shelf equipments,
- Complete closedness is not required,

The closed loops are realized only in the water and air reclamation. With these relaxations the construction cost will be greatly reduced.

The activities in the facilities mentioned above will attract public interest. The public may have opportunity to observe and even temporarily participate in some training if they are not disturbing the crew activity. The annex facility of Moon Park, therefore, is dedicated to student education and comprises the class rooms and dormitories.

All these facilities together with some amusement facility for temporary visitors constitute the Moon Park complex.

## TO THE MOON AND MARS: THE SPACE POLICY CHALLENGE

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Hardware is not enough to get anyone to the Moon or Mars. Bold manned missions can be carefully and brilliantly detailed technically, only to falter at the hands of hard-eyed budget officials.

The combination of a nascent station program, the Challenger disaster and space triumphs by countries other than the United States have generated a push to plan a coherent space strategy that need not be demolished and rebuilt with each change in administration.

If the United States hopes to forge ahead at a steady pace to develop outposts on the Moon and Mars, NASA and the space community must present plans that are acceptable to the administration, supported by Congress and comprehensible to the American public. These plans must make sense to all the players.

Thirty years after the genesis of NASA, a consensus has emerged from studies like the National Commission on Space's "Pioneering the Space Frontier" and the report written by Sally Ride. The new wisdom is 1) don't repeat the "stunt" that was Apollo, 2) make a conservative appraisal of a program's costs, and hold out for a large reserve, 3) and make sure you can explain clearly why the program is important--for example, the "logical step" that NASA says is the space station isn't necessarily logical to everyone.

This paper explores the lessons that can be learned from the Apollo, shuttle and space station programs--and from foreign programs--in anticipation of the next large steps by the United States into space.

Advanced Lunar Planning  
or  
Lunar Transportation Tradeoff Studies  
Economic Analysis of Water and Propellant  
from  
Phobos and Deimos

Raymond S. Leonard <sup>1</sup>

Previous work by the author and colleagues at Los Alamos National Laboratory established that it could be economically feasible to mine Phobos and Deimos for water. The launch costs from Earth to LEO at which such an undertaking might be profitable range from 400 to 3,200 dollars per pound of payload placed in low Earth orbit. Additional work established the costs for delivering water to the lunar surface.

Work which is underway as an independent research project and which will be reported on in this paper deals with the required market size. Depending on launch costs from Earth between 2,000 and 20,000 metric tons of water must be shipped from Phobos and Deimos per year in order to make it economically viable to establish a mine. The water can be used as is for life support or growing crops. If the water is electrolyzed then the resulting oxygen and hydrogen can be used for propellant. The end use, market need, and competition from other sources will affect the economics of the process.

The issues addressed in this paper are: what is the cost of lunar derived oxygen and other gases and what are the logistic considerations which might make one operation preferable to the other or whether a mine on Phobos and Demios would complement and Lunar gas plant.

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<sup>1</sup> President, Ad Astra, Ltd., Santa Fe, New Mexico

Lunar Surface Systems - Concepts and Integration  
**Robotic Mining Equipment for Lunar Resource Utilization**

Raymond S. Leonard,<sup>1</sup>

The paper describes the work accomplished as part of Ad Astra, Ltd.'s effort to develop robotic mining equipment for use on the Moon. A conceptual level system design, based on current technology and hypotheses, for extracting, moving and processing lunar soils and mineral resources will be presented. The design presented will be for producing the simplest possible product which will have a market potential on either the Lunar surface or in near Earth Space. The most probable products are oxygen, shielding materials and if the thru put rates are reasonable from a plant size standpoint, solar wind implanted volatiles. A major subsystem, the computer systems and software, will be described from a functional and networking standpoint. A developmental program which will involve private funding and field testing of the software on Earth based projects will be outlined. As part of the design development process the geophysical findings from research on the Apollo sample returns will be presented in form useful by engineers who will be designing the mining equipment, facilities and mining approach.

The paper will also outline the business strategy by which Ad Astra, Ltd. plans to finance, develop and deploy in actual earth based operations prototypes of the equipment concepts and software for eventual use on the Moon. The premise is that the development costs can be reduced and the final reliability of the Lunar mining system increased by making a number of small incremental advances to operating revenue producing systems here on Earth. This approach, which builds synergistically on private funding for commercial products offers an alternate path to developing components needed for a Lunar base.

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## Space Policy Issues

## A Different Race

## Space as a strategic alternative to the nuclear arms race

Raymond S. Leonard <sup>1</sup>

In this time of large deficits space exploration is often viewed as an expensive luxury which we can do without and strategic weapon systems as a wasteful but necessary evil. However by taking the time to look at the political objectives that are set forth for both a program of space exploration and for strategic weapon systems and applying a little creative thinking we can develop an alternative solution. The alternative would be based on re-programming funds allocated for new or upgraded strategic weapon systems to programs designed to build the infrastructure in space that this nation will need in order to remain free and prosperous in the 21st century. Some of the strategic factors will be cited and a comparison of alternatives will be presented.

One of the premises that this paper is based on is that we must stop viewing space as just a place to explore and research. Funding projects related to gaining access to space should be viewed as developing the next Alaska or another interstate highway system or air transport system. In addition space is becoming to be viewed as the high ground from a military standpoint. A robust and economically viable infrastructure in space will support at much lower costs the missions needed to deter a nuclear exchange.

Another premise which will be elaborated on in the paper is that funds spent on developing the infrastructure needed for space industrialization will eventually generate revenues while money spent on purely military systems consume capital and result in a decline in the capability of a nation to renew its revenue producing facilities. Several examples will be detailed.

A strong space program which establishes and maintains a nation as a pre-eminent space power confers many subjective benefits to a nation's ability to control foreign policy. In addition to enhancing national prestige a strong space program will provide us with the tools to macro-engineer the solutions to such problems as drought and famine in Africa, global energy shortages and environment pollution. Various example solutions will be set presented and explained.

Space is both a national and international resource. It should be developed by all nations with this viewpoint in mind. Strong space programs offer a nation a chance to demonstrate national excellence while helping all of mankind and achieving its strategic goals without harm to the world.

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## Lunar Resource Utilization

### Microwave Processing of Lunar Materials

Raymond S. Leonard<sup>1</sup> and Stewart W. Johnson<sup>2</sup>

The paper will report on the work accomplished as part of Ad Astra, Ltd's private research to develop construction materials for use in space out of lunar materials by using microwaves.

The work, which builds on previous basic research carried out at Los Alamos National Laboratory, addresses issues of concern to the design engineer who will design and construct a lunar base out of available resources. Some of the topics which will be addressed are: engineering properties of lunar regolith which has been sintered using microwaves; the amount of power required to sinter material into blocks approximately the size of a concrete block; joint and reinforcing details as well estimates of equipment sizes and weights for a plant capable of producing structural elements such as plates, shells, blocks and beams.

The paper will also outline the business strategy by which Ad Astra, Ltd. plans to finance, develop and deploy in actual earth based construction operations prototypes of the equipment and materials that will be eventually used on the Moon. The premise is that the development costs can be reduced and the final reliability of systems used to produce building materials for use in constructing space facilities or a Lunar base will be increased by making a number of small incremental advances to operating revenue producing systems here on Earth. This approach, which builds synergistically on private funding for commercial products and the prestige and promise of long term payback that comes from NASA sponsored SBIR projects, offers an alternate path to developing components needed for a Lunar base. Plans for building an experimental house using automatic equipment for producing and sintering adobe type bricks which will then be place using a robotic bricklayer will be described. The relationship between this demonstration project and a lunar base will be described.

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PARAMETERS FOR ELECTROLYSIS OF MOLTEN LUNAR ROCKS AND SOILS TO PRODUCE OXYGEN AND IRON; R. H. Lewis, L. A. Haskin, and D. J. Lindstrom, Dept. of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130

Electrolysis of molten lunar soil or rock is a direct means of extracting oxygen, provided that the conductivity of silicate is high enough. We have measured conductivities of simulated lunar materials and find that mare basalts with added ilmenite have high enough conductivities for practical cell design. We believe that a cell with the following characteristics could deliver one tonne of oxygen per 24-hour day. We use a 50:50 Apollo-15 mare basalt:ilmenite mixture as an illustration.

Assume a molten iron cathode and a Pt metal anode (which our experiments indicate should be stable against harmful oxidation). The surface area of each electrode is  $1 \text{ m}^2$  and the electrodes are 1 cm apart. The specific conductivity of the melt at  $1550^\circ\text{C}$  (such a high temperature is required because iron melts at  $1535^\circ\text{C}$ ) is  $4.8 \text{ ohm}^{-1}\text{cm}^{-1}$ . Assuming 60% efficiency (based on a measured lower limit for iron production),  $2.4 \times 10^5$  amps will be required at 5.0 volts, for a power of 1.2 megawatts. Of this amount, about 0.12 Mw will be used to reduce  $\text{Fe}^{2+}$  and oxidizing silicate to produce  $\text{O}_2$ , 0.6 Mw for melting and heating the feedstock, and 0.6 Mw in radiation loss. This leaves a shortfall of about 0.12 Mw, which can be made up by containment of part of the radiation loss or by moving the electrodes apart to increase the amount of IR heating and increasing the power by that amount. If electrolysis is done to the point of depleting half of the iron, the rate of flow of feedstock through a continuous-feed system would be about 0.5 cm/sec. By-products would include 1.75 tonnes of molten iron and 13 tonnes titanium-rich silicate melt.

These results indicate that there seems to be no intrinsic electrochemical problem with the production of oxygen by electrolysis; i.e., the values for these parameters fall within a realistic range. Actual cell design, mode of initial heating, and handling of feedstock and products have not yet been considered in detail. Variants of the process described above may be desirable. For example, an alternate design might be based on pure ilmenite feedstock entering a mare basalt melt (essentially a silicate flux) from which iron metal and oxygen are produced electrolytically and from which  $\text{TiO}_2$  crystallized. However, it may prove too difficult to remove the rutile which, in our experiments, formed as fine needles. In that case, some silicate would have to be present in the feedstock. On freezing, silicate glass filled with crystals of rutile might form a very strong ceramic.

## TOWARDS A LUNAR GLASS FIBER - METAL COMPOSITE: PRODUCTION;

William C. Lewis: GVSU, MI

Theodore D. Taylor, Robert Dalton, Todd Nichols:  
Clemson University, SC.

It seems likely that an entirely lunar derived glass fiber and metal composite with significant tensile strength is technically feasible. This composite and metals would be the only lunar derived materials safe to put under tensile loads in large structures. Technically feasible does not necessarily mean economical, however.

Production cost will depend on capital and operations costs. Lunar capital cost depends largely on imported plant mass; operations cost on labor, maintenance, and raw materials. Only capital cost will be considered here.

The plant accepts metal, unprocessed Apollo 16 composition regolith, and energy. It produces bulk composite. Mass flow is about 1 kg/sec. The plant uses solar process heat, and operates 1 week per lunar month, producing  $10E3$  kg of composite during the week.

Capital equipment is for material handling, glass melting, fiber generation, metal coating, and bulk composite handling. A 1 kg/sec mass flow will require only cable driven scoops. Glass melting requires refractories. If lunar refractories cannot be found, a platinum lined refractory vessel of perhaps  $1.6E3$  kg, holding about  $4.5E3$  kg of molten regolith is required. Melting 1 kg/sec of regolith requires about 2 Mw thermal, which will be provided by a solar array with area  $2E3$  square meters. Under lunar conditions, this may be feasible with a mass of 400 kg. Fiber generation requires a 4.6 kw DC motor massing perhaps 100 kg, and an associated generating mass of 24 kg. Energy for iron vaporization is about 400 kjoule/kg, and for iron melting about 4 kjoule/kg. Conservatively assuming 10% efficiency for vaporization and 30% for melting, one gets 4,000 kjoule/kg and 13 kjoule/kg for melting. Assuming electrical heating, vapor coating  $30E-6$  m diameter fibers with  $1E-6$  M of iron would require 830 kw and produce output containing 20% metal by mass; melting an estimated 80% metal by mass (glass being 20% by mass, 45% by volume) would require 10.4 kw. Related generating capacity masses are  $23E3$  kg for vaporization and 362 kg for melting. Material handling of the final composite does not seem a significant problem; the vaporization process would require light pressing forms, the melting process somewhat heavier casting forms. Form masses are not estimated.

Total mass plant masses are:  $2.5E3$  kg for melting,  $23E3$  for vaporization. These masses would be reduced if solar process heat could be used for metal, or if metal heating processes were more efficient. Melting uses about 4 times the metal; the energy costs of extracting metal will determine which process is economically favored.



LUNAR SURFACE MINING FOR AUTOMATED ACQUISITION OF HELIUM-3: METHODS, PROCESSES, AND EQUIPMENT; Y.T. Li and L.J. Wittenberg, Wisconsin Center for Space Automation and Robotics, University of Wisconsin-Madison, 53706

Lunar surface mining scenarios for producing helium-3 and other volatiles on the moon are being studied. The exploitation of the abundant lunar helium-3 resource as a nuclear fusion fuel could dramatically improve our energy future (1). Along with the production of helium-3, large amounts of by-products such as hydrogen, nitrogen and carbon dioxide themselves are significant for the space enterprise.

Maria rich in titanium are considered prime mining areas (2). In situ mining methods, which beam concentrated sunlight or microwave energy on the surface from a traveling vehicle to achieve thermal gas release, have been examined. They were rejected due to the poor heat conductivity of the regolith and the fact that escaping volatiles scatter isotropically instead of rising toward the surface.

Lunar surface mining and processing of regolith have three strategic options: (a) "traditional" central plant, (b) completely mobile system, and (c) mobile excavation-beneficiation-evolution chain with centralized volatile/isotopic separation. Our attention has focused on the last approach, since transporting tonnages of mineral over a distance in the lunar environment is highly not desired. An automated mining scenario is presented. A mobile miner which performs excavation, beneficiation, volatile evolution, as well as mineral handling will be described. The mobile miner has a bucket wheel front to remove the top 2 to 3 m of the regolith. The processed regolith is returned immediately to the mining site.

Three techniques for thermal evolution of volatiles have been evaluated in detail, namely: concentrated solar energy batch heating, microwave heating, and the fluidized bed techniques. In the first one, the concentrated solar energy is used to heat a medium such as helium-4 (by-product) in a cycling loop or lithium in heat pipes. The medium brings the heat to the layers of preheated regolith. A conservative estimation shows that 800 tonnes of beneficiated regolith can be heated from 300°C up to 650°C within 34 minutes in a 20 × 10 × 2.5 m module. Dividing the regolith into layers in the module is not needed in the second technique since the penetration of the microwaves is excellent. Gravitational flow of the regolith in the module is sufficient. However, it requires electrical energy supply and an energy conversion scheme must be involved if solar radiation provides the energy source. In the third technique, high temperature helium-4, heated also by the solar energy, is used to heat the granules of the regolith directly. A mixture of the helium-4 and evolved volatiles is continuously directed into a small side stream, where the volatile gases are separated. Estimates show that a bed 2 m dia. × 4 m high can process particles <250 µm dia. at the rate of 100 kg/s yielding 20 kg of helium-3 per year. Finally, our study indicates that recovery of the heat is necessary for each of the thermal evolution mechanisms

- (1) Wittenberg, L.J., Santarius, J.F., and Kulcinski, G.L. (1986), Fusion Technology, Vol. 10, p. 167-178.
- (2) Cameron, E.N. (1987), WCSAR-TR-AR3-8708.



PHYSICAL PROPERTIES OF CONCRETE MADE WITH APOLLO 16 LUNAR SOIL SAMPLE;  
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On March 6, 1986, the National Aeronautics and Space Administration awarded Construction Technology Laboratories with 40 grams of lunar soil. These samples were to undergo special testings to evaluate the feasibility of using lunar soil as an ingredient for concrete on a proposed lunar-based construction program. Two types of investigations were performed. One was to evaluate the performance of lunar soil as an aggregate for concrete and the other was to determine the physical properties of concrete made from this soil.

Prior to use, portions of the lunar sample were microscopically examined to determine their petrologic characteristics. The samples were also analyzed with the scanning electron microscope to determine their morphology and elemental composition. The lunar soil appeared to have good characteristics as a fine aggregate. High alumina cement and distilled water were then mixed with the lunar sample to make a 25 mm cube, a 13 mm cube and three 3x15x80 mm slab specimens. Tests were performed on these specimens to determine the compressive strength, the modulus of rupture, the modulus of elasticity and the thermal expansion coefficient. The results are as follows:

Compressive strength: 75.7 MPa;  
modulus of rupture: 8.3 MPa;  
modulus of elasticity: 21,400 MPa;  
thermal expansion coefficient:  $5.4 \times 10^{-6}$  cm/cm/c

It was concluded that lunar material can be used as an aggregate for concrete construction on the moon.

# CONCRETE LUNAR BASE INVESTIGATION

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The objectives of the project are to perform structural analyses and a preliminary design of a concrete lunar infrastructure and to evaluate technical and economic feasibility of the concept. The study also documents issues such as utilization of lunar resources for concrete production, needed facilities, construction technique, safety considerations and a prototype test model.

The proposed structure is a three story cylindrical, precast, prestressed building 120 ft in diameter and 72 ft high. The structure was designed to withstand a one atmosphere internal pressure and to provide 33,000 sq ft of work area suitable for scientific and industrial operations.

Engineering data on lunar concrete needed in the structural analysis were taken from test results obtained in a previous research program, "Physical Properties of Lunar Concrete Made with Apollo 16 Lunar Soil." The design procedures basically followed the ACI 318-83 Building Codes. All loads, except internal air pressure were calculated for 1/6 g to account for the weak lunar gravitation.

Three loading conditions, including during construction, at full pressurization, and in the event of an air-leak, were studied. The result of the study indicates that the internal air pressure is the most critical, particularly for roof and ground-floor slabs.

To minimize the slab thicknesses, tension columns connecting roof and ground slabs at maximum moment locations were designed. The tension columns will act as a tension member under a pressurized condition and as compression member in a zero pressure condition.

Records indicate that the depth of lunar regolith varies from 0.5 m to about 40 m in mare and highland regions. Lunar soils are absolutely dry and in general have high porosity (45%) and low cohesive strength (0.1 to 1.0 kN/m<sup>2</sup>). These mechanical properties of soils make conventional foundations impractical for construction on the moon. To avoid differential settlements of the structure, a floating foundation was developed. The foundation is a dish-shape substructure made with precast concrete members, capable of having rigid body rotations and translations as the lunar soils beneath it yield.

RADIO ASTROMETRY FROM THE MOON; R. P. Linfield,  
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The technique of Very Long Baseline Interferometry (VLBI) allows very accurate radio astrometry. Observations over the last 10 years by JPL and GSFC have yielded catalogs of 50-150 sources north of declination -30 degrees, with positions known globally to about 2 milliarcseconds (mas). Some further improvement in accuracy is possible, but three major error sources impede progress. They are the following: source structure effects, spatial and temporal variations in tropospheric delay, and cm-scale motions (deformations and rotation irregularities) of a dynamic earth. The first effect can be reduced by using higher observing frequencies, but the other two are more fundamental for earth-based observing. Observations from earth-orbit avoid tropospheric problems. However, uncertainties in the evolution of the vector separation between antennas may be at least as serious as on the surface of the earth.

The moon can provide a stable platform in vacuum for radio astrometry. Lunar motions have a very much smaller stochastic component than terrestrial motions, and can be specified very accurately from planetary ephemerides and approximately 20 parameters peculiar to the moon. These parameters can be determined as part of a global solution to astrometric observations. The ultimate accuracy of an astrometric catalog of compact extragalactic radio sources from lunar observations will be better than 500 microarcseconds. It may well be better than 100 microarcseconds. This catalog would form an inertial reference frame of extreme stability and accuracy. In combination with optical data, it would allow an absolute measurement of stellar and planetary motions. In combination with differential VLBI measurements from earth or space, it would allow extremely precise navigation of spacecraft.

LUNAR BASE MISSION TECHNOLOGY ISSUES AND ORBITAL DEMONSTRATION REQUIREMENTS ON SPACE STATION; C. P. LLEWELLYN, SELF CORPORATION, 427 WESTON ROAD, GRAFTON, VA 23692 AND DR. D. J. WEIDMAN, NASA LANGLEY RESEARCH CENTER, MAIL STOP 288, HAMPTON, VA 23665.

In early 1987, the Office of Aeronautics and Space Technology, NASA Headquarters, requested that the LaRC Space Station Office perform a study to assess the impact of a manned lunar base mission on the IOC Space Station. An agency-wide team was formed to investigate the Space Station support necessary to accommodate such a mission with emphasis on precursor research requirements, lunar mission support requirements in LEO, concurrent science applications, technology requirements/issues, and station resource requirements including crew, power, and volume.

From a review of recent studies conducted by NASA and in concert with the Civil Space Leadership Initiatives activities, a baseline lunar base mission scenario was postulated and the top level technology requirements/issues needed to support such a mission were identified. These top level issues were then analyzed to determine technology areas needing early or "accelerated" emphasis, and a statement of near-term and far-term requirements was formulated in terms of applicability to the lunar base initiative. From this analysis, the systems level technologies that were considered enabling were identified and an orbital demonstration/verification program for the major flight hardware elements of the lunar vehicle was developed.

This paper will concentrate on the technology requirements/issues, the on-orbit demonstration and verification program, and the Space Station focused support required prior to the establishment of a permanently manned lunar facility. Technology issues associated with the on-orbit assembly and processing of the lunar vehicle will also be discussed.

Key lunar base mission technology implications are summarized in terms of the IOC Space Station support requirements and on-orbit support activities. Technology areas requiring additional study are identified and include in-space processing/serviceability, space cryogenics, and automated rendezvous and docking. Some basic requirements for an OMV-type vehicle with increased capability and operational flexibility are presented.

## AN APPROACH TO THE DESIGN OF A HEALTH CARE DELIVERY SYSTEM FOR LUNAR BASE

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Terrestrial experience in remote operational environments (Antarctica, nuclear submarines, ships at sea, STARPAC, etc.) has provided important lessons regarding health monitoring and telemedicine. The currently envisioned space station Health Maintenance Facility (HMF) will embody the latest conceptual and technological advances in telemedicine and will serve as a valuable "test bed" for space medicine. The design, construction, and operation of a self-sustaining health care delivery system for lunar base will present significant challenges to medical planners. A multidisciplinary approach involving both generalists and specialists in the fields of medicine, surgery, biomedical engineering, aerospace physiology, environmental toxicology, and space operations is advocated. Although an extension and expansion of space station medical technologies may satisfy many of the requirements for a lunar medical facility, the lunar environment and mission scenarios will undoubtedly demand fundamentally different strategies for crew training, medical staffing, general surgery, rescue/recovery, computer assisted diagnosis/medical management, and a host of other issues ranging from the shelf life of medical expendables to exercise countermeasures.



LUNAR WASTE HEAT RADIATOR DESIGN

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A concept for a proposed lunar waste heat radiator (LHWR) is discussed. The major design requirements are to minimize mass delivered to the lunar surface and to provide potential integration with other systems. The radiator takes advantage of the pre-existing Earth and Space technology bases to give a near-term low risk development program while exploiting lunar resources.

The LHWR uses a two phase system with lunar derived silica glass for the radiator and water vapor as the preferred working fluid. The major benefit of this design is the increase in specific power, by a factor of ten, caused by the drastic reduction in mass of the working fluid. Use of a liquid water film, as the radiating surface, has the additional benefit of a large emissivity ( $\epsilon_r = 0.955$ ) without the use of emissive coatings. This benefit is retained by the use of silica as the radiator containment since its transmittance is also high ( $T_w > 0.9$ ).

Integration of the system is discussed both in terms of system use and lunar manufacturability. It is shown that pipe and structural element fabrication can be integrated and that water for cooling can be integrated in the overall water handling system. The possibility of integrating the radiator into a building structure is shown to have benefits in reducing mass and day/night variability.

Various techniques for protection from meteorites, radiation and cyclic heating and cooling are evaluated. Operating concerns such as variability in heat load, different radiator temperature requirements and possible failure modes are shown to be critical design parameters.

**Long Term Lunar Base Operation: Some Ecological Considerations.** Bassett Maguire, Jr. and Kelly W. Scott. Department of Zoology. The University of Texas at Austin. 78712

A major factor for long term success of a lunar station is the ability to keep an agro-ecosystem functioning at a desirable, stable steady state (with ecological stability and reliability). This paper discusses some ecological features which will be needed if the required steady state of the ecosystems are to be maintained. Long term extra-terrestrial, manned stations which are not close enough to earth to be provided with continuous supplies of food, oxygen, and water will share a set of characteristics including needs for an adequate supply of power, agricultural systems for food and oxygen production, and recycling systems for the stations' wastes. Also, interactions will occur between all of the functional components of a lunar station, for example between the agricultural and waste disposal sub-systems. Therefore it is important to begin to consider these interactions so as to design each of the various sub-systems in such ways that the desired functions of other sub-systems are aided (or at least not compromised). The ecological structure, both abiotic and biotic, of a lunar station will determine its overall stability and ultimately its ability to function as a long term human life support system.

Four primary requisites of the station's agricultural and recycling systems are: diet adequacy, recycling and purification adequacy, high productivity, and ecosystem reliability. Most designs and models of controlled ecological life support systems (CELSS) are modular, wherein food producing systems, human living areas, recycling and other systems are isolated from each other. Such physical isolation may be straightforward, but it will be very difficult to isolate these systems from each other microbiologically. Plants produce external organic materials with the result that the rhizospheres and leaf surfaces of terrestrial plants contain well developed communities of bacteria and fungi. Ecological theory suggests, and ecological observation and experiments show that some species sets of micro-organisms protect plants and thereby improve plant productivity and their ecosystem's stability and reliability. The microbiota does this by buffering the plants against biological and environmental perturbations. Other microbial species sets will damage the plants and reduce desired ecological stability and reliability.

While it is possible to eliminate plant-associated microbiological communities by growing the plants aseptically, it is not practical to keep the plants germ-free on a large scale if humans are working with them. One important task therefore is to assemble and maintain stable, desirable microbial communities which will protect the plants.

A powerful way to increase ecosystem reliability is to utilize buffering systems. A very effective physico-chemical and biological buffer in a lunar station could be a carefully designed and maintained (lunar derived) soil. A soil increases the structure of the agro-ecosystem and would provide ion exchange sites which buffer what would otherwise be large element and compound fluctuations (of nutrients, wastes, etc.). Soils buffer temperature level and atmosphere composition. In addition, there is considerable ecological theory which strongly suggests that some kinds of communities of organisms are very effective in increasing the stability of ecosystems. Such ecosystems change less as a result of a given shock or perturbation than do other ecosystems. Soils provide the variety of kinds of habitats required for more versatile and beneficial soil micro-organism communities, thereby providing effective microbial buffer systems. We are currently doing experiments to learn more about these ecological dynamics and to extend ecological theory concerning them.

# THE EXPANDABLE PLATFORM (WITH BUILDING STRUCTURES THEREON) AS A LUNAR BASE

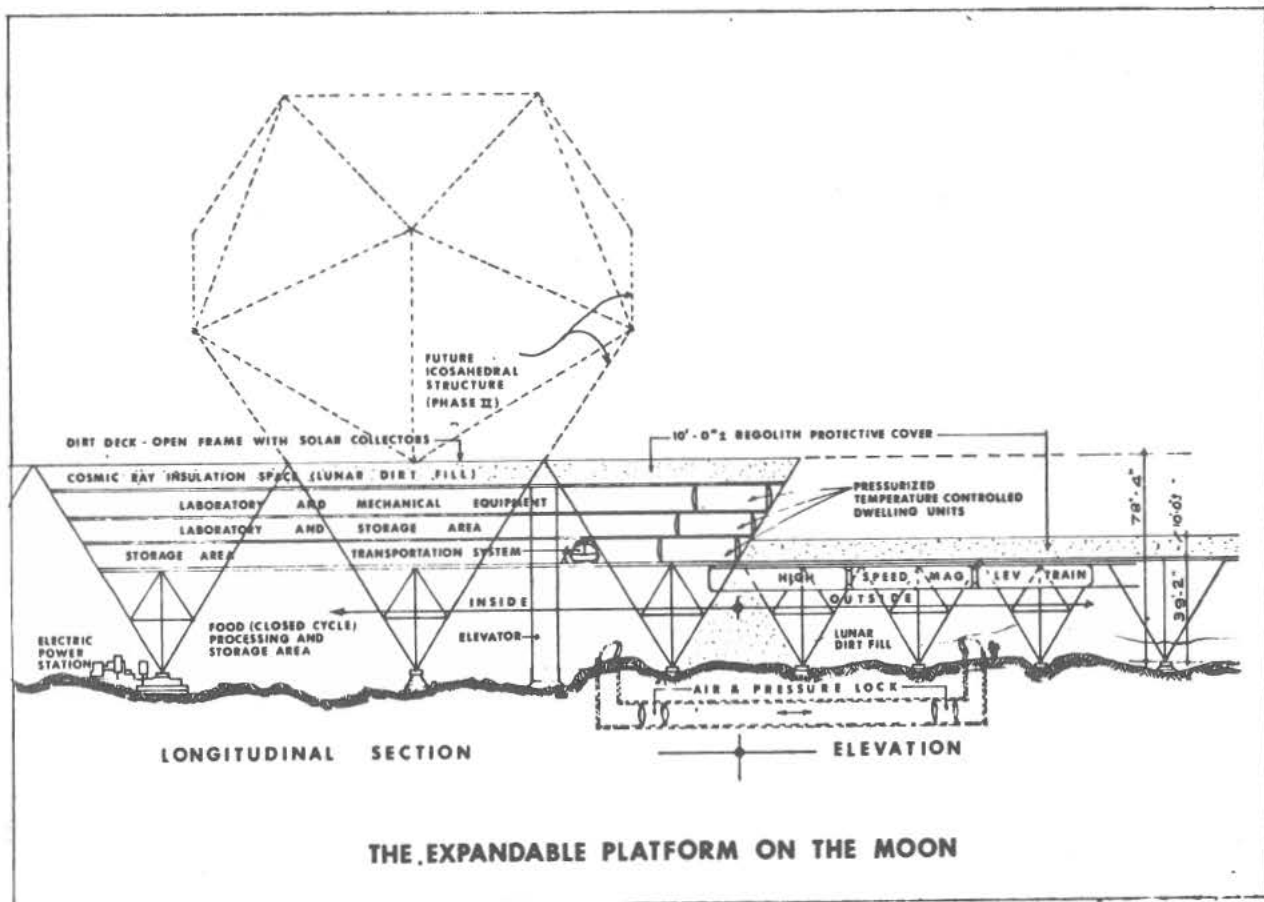
Joseph J. Mangan

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There is a need for a new basic structural form that can be placed on the surface of the moon. It must have maximum structural efficiency, be redundant, programmable, expandable and be capable of providing enclosure for all necessities required at a lunar base. It must also have a capability to be eventually constructed of materials from the moon.

The Expandable Platform with its capability for multiple and varied uses on earth can be made into a simple open framed structure with an inbuilt shape that provides protection from the harsh temperatures and irradiated environment of the moon.

The Use of the tetrahedral frames of the Expandable Platform makes not only the most efficient possible type of construction but also the most efficient surface-placed moon base with the capability to provide the necessary transport links to other sites using the same redundant tetrahedral frames. Both the base and the transport links are expandable.



## **Electric Potential and Fields at the Lunar Surface: Implications for a Lunar Plasma Observatory**

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The surface of the Moon is certain to have electric potentials, and associated fields, determined by the varying lunar space environment; in addition to being a basic feature of the lunar surface, these potentials may affect manned activity or scientific experiments on the Moon.

We present the factors that determine the electric potential and fields at the surface of the Moon, and show the results of theory and experiment that give these potentials and fields for a variety of space environments encountered in the lunar orbit. In its orbit the Moon is exposed to the flowing plasma and associated electric and magnetic fields of the solar wind. The Moon also passes through the confined plasma and fields of the extended tail of the Earth's magnetosphere. Also influencing the local charge balance and thus the potential are the intense solar spectrum of visible, UV, and X-radiation incident on the surface.

Electric fields at the surface are due to a surface potential resulting from the balance between local charging processes including photoionization and incoming plasma fluxes. These processes will be discussed, as will the expected range of potential and field values.

However, due to the changing plasma environments encountered in the lunar orbit, the potential may vary more rapidly than originally thought, especially as the Moon traverses the geomagnetic tail of the Earth. In this magnetotail, two quite different plasma regimes can be encountered: the relatively low density and cool lobe regions, or the higher density and hotter central plasma sheet. In addition, there is strong evidence that large, moving plasma structures, known as plasmoids, are associated with magnetospheric storms and can be encountered in the geomagnetic tail.

In particular, it appears possible that some plasmoids could be much larger than the dimensions of the Moon, implying that the Moon is likely to be enveloped if a plasmoid sweeps by when the Moon is in the geomagnetic tail. Because of the recent results from two intensive, international Coordinated Data Analysis Workshop (CDAW) series, we are able to better determine the characteristics of such rapidly moving plasmoids and their possible range of sizes. We show examples of the evidence for plasmoids and calculate their effect on the lunar surface potential.

Finally, the possible use of a base on the Moon as a Lunar Plasma Observatory will be discussed, as will some possible implications of the surface potential on manned and scientific activities at such a base.



## CRASHPORTING MATERIALS FROM L-1 TO LUNAR FACILITY

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Less than a kilogram of fuel is needed to crash 100 kg of "cargo" onto the surface of the Moon from L-1, while to soft-land that much cargo about 90 kg of fuel is expended. The building and operation of a LUNAR-COLONY-BASE will require the import of much material which is not obtainable on the Moon. If lunar water is not available a majority of such imported mass will be hydrogen and/or hydrogen compounds such as hydrocarbons, ammonia, etc. If water is easily obtained on a moon of Mars such Phobos (PHobos, Deimos) water could be transported to a L-1 base whereat it is electrolysed and the hydrogen crashported to Luna. <sup>(1)</sup>\*

At L-1 aluminum alloy and plastic scrap from "surplus" rockets and tanks plus ellipsoids and cryogenic solids are manufactured into 100 kg crashloads. <sup>(2)</sup>\* Such crashed onto the Moon "cargo" are recovered from a ten meter diameter impact chamber in which crashloads seriatim crash into a debris assembly of several tonnes that has been thrown toward the chamber's center. That debris assembly is mostly of "soft" lunar materials such as CaO and MgO as loose particles.

A 100 kg crashload might have a 5 kg outer shell of aluminum alloy, 14 kg of foamed plastic, 10 kg of ammonia ice, a 20 kg ellipsoid, 1 kg of control equipment, and 50 kg of hydrogen ice.

The ellipsoid has a very tough and thick metal shell surrounding special substances which can withstand such crashing. The shell metals and special substances are of elements not found on the Moon but very important for lunar industrialization.

The solid materials of the fragmented crashload become mixed with the debris assembly. The ellipsoid and larger fragments are withdrawn before the arrival of the next crashload. With a period of about a hundred minutes between crashloads about 500 tonnes a year is crashported from L-1 to that lunar facility.

Upon crashing the ammonia and hydrogen become gases and those gases flow into large chambers and facilities wherein the gases and dust particles are separated and processed.

The crashload is a "smart" missile and has very small rocket engine(s) and electronic means which enable the lunar radar-controlling system to direct it through an opening of less than a square meter into a short passageway of the large impact chamber at a velocity of almost 2.4 km/s.

There is at least one very quick acting shutter in that passageway and also there could be a disposable shutter of very thin aluminum alloy through which the crashload blasts a hole that is less than a tenth of the disposable shutter's area. A new disposable shutter, made mostly of scrap from used shutters is installed when the vapor pressure remaining in the impact chamber is less than a couple of mm of Hg.

If recoverable water is found on the Moon this type of facility could be used for importing larger ellipsoids, ammonia, plastic and aluminum scrap, etc.

<sup>(1)</sup>\* O'Leary, B. SPACE MANUFACTURING 5 Pages 41-48 (1985)

<sup>(2)</sup>\* Marwick, E.F. AIAA-86-1848 Pages 1-8



## LEO ENERGY FROM MOON MATERIALS- E.F.Marwick, Inventor

A kilogram of lunar material when caught by a Low Earth Orbiting (LEO) satellite-facility could cause the production of about a kwh of electrical energy; Or that capture of a kg could give horizontal orbital velocity to about 435 grams of mass that has been shot 200 km straight up from Earth. When captured by that LEO satellite-facility those 435 grams gain over 3.6 kwh of kinetic energy.\*<sup>(1)</sup>\*

In addition, in both cases, that kilogram of lunar material remains in that LEO satellite-facility. Unless there is aerobraking the soft-docking of such a kilogram of lunar material requires the additional expenditure of over 1.4 kwh of kinetic energy. Such electricity or kinetic energy comes from the fact that a kilogram on the lunar surface has about 17.4 kwh of potential energy above the surface of the Earth and a kilogram 200 km above the Earth's surface has about .54 kwh of potential energy while an orbiting kilogram at that altitude has about 8.3 kwh of kinetic energy.

The addition of about .73 kwh of kinetic energy to a kg of mass on the lunar surface in a specific direction will cause that kg to be in an orbit which touches the circular LEO orbit of that satellite-facility. When a kg from Earth is shot straight up with about .54 kwh of kinetic energy (assuming no losses) it has at its apogee, which is on that LEO orbit, a velocity which is about 7.36 km/s less than the satellite-facility.

The momentum loss by that satellite-facility when it captures 435 grams of earth-mass is equal to the momentum gain from the capture of a kilogram of moon-mass. If the satellite captures an excess of lunar materials it gains momentum and rises to a higher altitude. If it captures only earth-mass it loses momentum and will fall to a lower average altitude.

Thusly it is possible to have an orbital transfer vehicle which can transport gently many thousands of tonnes of cargo from a lower Earth orbit to a higher Earth orbit by capturing many separate packages of lunar materials (crashloads). At the desired orbit the OTV discharges that cargo and also materials from those captured crashloads. The OTV returns to lower Earth orbit by capturing crashloads of Earth-materials or by capturing retrograde traveling lunar crashloads.

It is possible that such an OTV could transport many thousand tonnes of supplies and equipment from Earth from LEO to GEOSynchronous orbit and that OTV with the captured lunar materials remains in GEO while most of the cargo from Earth is solar-sailed to L-1, etc. The OTV could then be a GEO satellite-facility capturing lunar crashloads both prograde and retrograde.

It is possible to obtain much electricity by a LEO satellite that has a long vertical tether of conducting material (Electrodynamic System).\*(2)\* The tether is a very high velocity conductor traveling through the Earth's magnetic field and ionosphere. Such a satellite loses altitude with the generation of electricity. Hence a LEO satellite facility gains about a kwh of electricity by the capture of a kilogram of lunar material.

\*<sup>(1)</sup>\* Marwick, E.F. AIAA-86-1848 Pages 1-7

\*<sup>(2)</sup>\* Bekey, I ASTRONAUTICS AND AERONAUTICS Apr.1983 p 34

Ten Years of Living Off the Land:  
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Space futurists from Konstantin Tsiolkowsky to Dandridge Cole have discussed the possibility of using non-terrestrial materials for space construction and industry. In 1974, O'Neill proposed the construction of large space structures such as solar power satellites and habitats from lunar material (Reference 1). In the late 1970s NASA conducted two major summer studies on space industrialization using lunar resources as feedstocks (Refs. 2 & 3).

In order to guarantee continuation of work in this area the private, non-profit Space Studies Institute was founded in 1977. SSI has conducted research into mass drivers, coaxial electromagnetic accelerators which can be used to launch raw lunar material into free space from the Moon's surface. Three prototype mass drivers have been constructed at MIT and Princeton University with accelerations ranging from 33 gravities to 1800 gravities.

Under SSI contract, bench-scale chemistry required to process lunar soil into constituent elements via an HF acid leach process has been demonstrated. In 1986 the Institute published the design of the solar power satellite constructed from lunar materials. Over 99% of the SPS is lunar and the resulting design has only 8% more mass than the earth baseline SPS studied in the NASA/DOE SPS project. Present projects at the Institute include glass/glass composites from lunar material, an investigation into the use of beamed energy for space propulsion (possibly as a means to "bootstrap" future solar power satellites), the creation of an economic model for space resources utilization and relatively low cost probes which can search for trapped volatiles at the lunar poles.

The information from these studies was given to the members of the President's National Commission on Space and is reflected in the recommendations of that body. Future Institute projects include a 1988 Lunar Resources Systems Study and the design and construction of pilot plants for glass production power storage and lunar oxygen processing.

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PRELIMINARY DEFINITION OF A LUNAR LAUNCH AND LANDING FACILITY (COMPLEX 39L); H. D. Matthews, NASA Kennedy Space Center, Florida 32899; E. B. Jenson and J. N. Linsley, Florida Institute of Technology, Melbourne, Florida 32901

NASA advanced planning proposes a lunar base scenario incorporating scientific research and in-situ resource utilization. Applying a baseline transportation fleet, the launch and landing requirements to implement the proposed lunar base scenario are analyzed. The transportation requirements are assumed large enough to warrant the existence of a lunar launch and landing facility. From an operations analysis, a project design for the launch and landing facility is achieved. Innovations in the areas of unmanned cargo launch, interconnection of launch and landing activities with other lunar base activities and native resource utilization are considered. The facilities and operations are then studied to determine top-level launch and landing facility requirements such as: manpower, mass, and power.

**LUNAR MINING AND CONSTRUCTION: A STATUS REPORT**

Lisa A. McCauley\* and Patricia M. Watson\*\*

Construction and mining technologies will be required for lunar base development and operational activities. Typical applications include site preparation for facility construction, rock and soil moving for materials processing, and drilling for science experiments. Required mining activities will encompass materials handling, drilling, rock fragmentation, and dust collection. The lunar environment and lunar surface characteristics will drive the design and development of mining equipment and techniques. Lunar characteristics especially challenging to equipment designers include a high vacuum, low gravity, and harsh thermal environment. Initially, all machinery will be brought from Earth, which means that equipment must be lightweight, highly reliable, and multifunctional. Other equipment development issues include the effects of the lunar environment on system requirements (e.g., mass, lubrication requirements, etc.) and the appropriate application of automation and robotics technologies.

This paper provides an assessment of the state-of-the-art of mining and construction technologies and equipment required for lunar base development. Pre-Apollo research, Apollo scientific data, and post-Apollo sample analysis are reviewed. The current understanding of lunar soil and rock conditions is presented, as are environmental concerns, such as volatiles, atmosphere, potential for dust levitation. The status of mining technologies and equipment is reviewed for terrestrial development and operational activities and for lunar research and development. In particular, fragmentation, materials handling, and ore crushing are emphasized. Research and technology needs, such as materials and power requirements, are identified. The paper closes with the authors' conclusions and recommendations regarding the status and future direction of lunar mining development.

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POTENTIAL NEW RELATIONSHIPS BETWEEN THE PUBLIC AND PRIVATE  
SECTORS FOR THE JOINT DEVELOPMENT OF SPACE

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On January 28th, 1987, fifty representatives from the private and public sectors met in Lake Buena Vista, Florida to discuss potential joint development of the key technologies and mechanisms that will enable the permanent habitation of space. Specifically, this workshop was an initial step to develop a joint public/private assessment of new technology requirements of future space options, to share knowledge on required technologies that may exist in the private sector, and to investigate potential joint technology development opportunities.

This workshop represents the first "nucleation" phase, of a continuing process. The participant list is far from a complete list of all organizations that will make significant contributions in space development technologies and activities. We are striving only to bring together a representative cross-section of business, academic and government organizations to investigate the feasibility of potential technology developments and the organizational structures that would most effectively bring them to fruition. If it appears that the timing is correct for this sort of activity, we can then consider the "implementation" and "production" phases, where the entire national -and perhaps international - corporate, academic, and public communities will have an opportunity to participate.

This paper presents the results of this workshop and details plans for future activities.



**APPLICATIONS FOR SPECIAL PURPOSE MINERALS AT A LUNAR BASE;  
D. W. Ming, NASA Johnson Space Center, Mail Code SN12, Houston, Texas 77058.**

Maintaining a colony on the Moon will require the utilization of lunar resources to reduce the number of launches to transport goods from the Earth. It may be possible to alter lunar materials to produce minerals or other materials that can be used for applications in life support systems at a Lunar base. For example, the mild hydrothermal alteration of lunar basaltic glasses should produce special purpose minerals (e.g., zeolites, smectites, and tobermorites) which in return may be used in life support, construction, waste, and chemical processes.

Ming and Lofgren [1] have synthesized zeolites, smectites, feldspars, feldspathoids, and tobermorites by mild hydrothermal alterations of synthetic basaltic glasses with chemical compositions similar to lunar basaltic glasses. Zeolites, smectites, and tobermorites have a number of potential applications at a lunar base. Zeolites are crystalline, hydrated aluminosilicates of alkali and alkaline earth cations that possess infinite, three-dimensional crystal structures. They are further characterized by an ability to hydrate and dehydrate reversibly and to exchange some of their constituent cations, both without major change of structure. Based on their unique adsorption, cation-exchange, molecular sieving, and catalytic properties, zeolites may be used as a solid support medium for the growth of plants [2], as an adsorption medium for separation of various gases (e.g.,  $N_2$  from  $O_2$ ), as catalysts, as molecular sieves, and as a cation exchanger in sewage-effluent treatment, in radioactive-waste disposal, and in pollution control. There are other possible applications for zeolites at lunar or other planetary bases, but, they are too numerous to report here. Smectites are crystalline, hydrated 2:1 layered aluminosilicates that also have the ability to exchange some of their constituent cations. The potential use of smectites at a lunar base may be somewhat less favorable than the use of zeolites. As is the case with zeolites, smectites may be used as an adsorption medium for waste renovation, as adsorption sites for important essential plant growth cations in solid support plant growth mediums (i.e., "soils"), as cation exchangers, and other important uses; however, zeolites have up to five times more capacity to exchange cations than smectites. Tobermorites are crystalline, hydrated double-chained layered silicates that have cation-exchange and selectivity properties intermediate between those of smectites and most zeolites. Tobermorites may be used as a cement in building lunar base structures, as catalysts, as mediums for nuclear and hazardous waste disposal, as exchange mediums for waste-water treatment, and other potential uses.

Special purpose minerals synthesized at a lunar base may also have important applications at space station and for other planetary missions. For example, zeolites or tobermorites might be used in waste renovation on the space station or wastes may be sent to the lunar surface and processed at a lunar base which utilizes these special purpose minerals for waste recycling. New technologies will be required at a lunar base to develop life support systems that are self-sufficient and the use of special purpose minerals may help achieve this self-sufficiency.

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**EARTH BASED LUNAR SOIL PROCESSING PILOT PLANT: AN OPERATIONAL  
PROFIT CENTER AND FINANCIAL MODEL, William F. Mitchell, Lady Base One  
Corporation**

Lady Base One Corporation is implementing plans to put a full-scale, 850 ton per day lunar soil processing pilot plant into operation on the Houston ship channel in Pasadena, Texas. Phosphogypsum has been chosen as a lunar soil substitute because it has similar chemical and physical characteristics to lunar soil and can be obtained in commercial quantities.

The goal of this project is to demonstrate an economically feasible process for the thermal decomposition of phosphogypsum for production of sulfur dioxide gas and a saleable solid by-product that precisely equates to the thermal decomposition of lunar soil to produce oxygen and saleable solids. The process in both cases has been extensively studied with numerous laboratory and theoretical examples of enabling technology. However, no commercially viable plant exists and, therefore, the lessons learned in the development of the pilot plant can serve as a model to directly benefit the development of the lunar base itself.

The pilot plant will be a profit center designed to serve as a financial model to relate a complicated new lunar venture proposal to a familiar venture where risk and return on investment can be calculated and easily understood. The methods used to finance the pilot plant will subsequently be used to finance the lunar plant.

There are many significant correlations between the model and the actual lunar facility. They have similar products, markets, sales volumes and technological process uncertainties. Both have high degrees of financial risks in the start-up phase. Their economic advantages are due to superior locations relative to the target customers. Each claims the ability to deliver products at lower prices than their competition. They even have comparable ambitious and optimistic time frame challenges.

The major obvious difference is the mature versus the developmental nature of the transportation and habitat facilities. However, even this area can be shown to be comparable in that competent and reputable companies are willing to provide the needed transportation and habitats by contract. Most other differences are in scale i.e., a cost of \$20 million for the pilot plant versus \$20 billion for the lunar plant; a sales price of \$150/ton for the model's products and \$150,000/ton for lunar products.

As of September 1987, progress on the project is substantial. The lead technical staff has been contracted, the plant site has been leased and a long-term raw material supply agreement has been obtained. The legal, accounting and financial consultants expect the business plan to be ready to submit for financing in early October 1987.

The pilot plant is expected to perform timely and produce the necessary profits needed to be financable. In addition to providing a technological and financial model, the success of the project will further establish the track record of the developer's ability to initiate and execute projects that will enhance the skills needed to develop the Moon.

"THE LUNAR ROVING VEHICLE" --- A HISTORICAL PERSPECTIVE

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As NASA proceeds with its studies, planning and technology efforts in preparing for the early 21st Century, it would seem appropriate that one should reexamine past programs for potential applicability in meeting future national space science and exploration goals and objectives. Both the National Commission on Space Study (NCOS) as well as NASA "Sally Ride Study" suggest future programs involving returning to the moon and establishing man's permanent presence there, and/or visiting the planet Mars in both the "unmanned" and "manned" mode. Regardless of when, and which of these new bold initiatives is selected as our next national space goal, implementing these potentially new national thrusts in space will undoubtedly require the use of both manned and remotely controlled roving vehicles.

Therefore, the purpose of this paper is to raise the consciousness level of the current Space/Exploration planners to what in the early 1970's was a highly successful roving vehicle. This vehicle, the Lunar Rover (LRV) was designed for carrying two astronauts, their tools and equipment needed for rudimentary exploration of the moon during the Apollo program. The paper contains a reasonably comprehensive discussion of the vehicle, its characteristics, and use on the moon. Conceivably the LRV has the potential to meet some future requirements, either with relatively low cost modifications or, via an evolutionary route. This aspect, however, is left to those whom would choose to study these options further.

## SPACE HABITABILITY CONCEPTS: 21ST CENTURY

F.E. MOUNT AND W. R. JONES II

NASA/JSC

Habitability areas have been baselined for a Space Station which is compatible for launch via the Shuttle. Requirements and specifications are already in place for this configuration.

One-g, .7g and micro-g drive the designs and concepts of Crew Quarters and other habitability areas for crew use. Gravity would necessitate an interior design different than the current Shuttle-compatible design. With a gravity, there would be a requirement for sleep accommodations in a horizontal plane, which would increase the horizontal dimension provided for sleep accommodations, over that in the current Space Station.

Use of a heavy lift launch (HLLV) would change the size of the cylinder used for the habitation modules. This size difference would influence the size and topology of the interior habitable volume. Constraints imposed for long-term missions, such as mass and volume considerations would (could) reprioritize some of the decisions made for the Space Station configuration.

Concepts and thoughts are presented covering future Missions to Mars and Lunar Bases.

LUNAR LANDER STAGES

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PD32

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This paper will examine the lunar lander stages that will be necessary for the future exploration and development of the Moon. Lunar lander stage sizing will be discussed based on the projected lunar payloads listed in the civil needs data base. Factors that will influence the lander stage design will be identified and discussed. Some of these factors will be; lunar orbiting and lunar surface lander bases; implications of direct landing trajectories and landing from a parking orbit; implications of landing site and parking orbit; implications of landing site and parking orbit selection; the use of expendable and reusable lander stages; and the descent/ascent trajectories. Data relating to the lunar lander stage design requirements to each of the above factors and others will be presented in parametric form. This data will provide useful design data that will be applicable to future mission model modifications and design studies.



## Radiological Health Considerations for a Lunar Base

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A base on the lunar surface will be continuously irradiated with a flux of about 17,350 energetic charged particles/m<sup>2</sup> every second. This flux of Galactic Cosmic Radiation (GCR), which consists of energetic protons (90%), helium nuclei (9%), and heavier ions (1%), produces a dose to the blood forming organs (BFO) of about 0.06 gray (Gy) per year (6 rad/yr). although there are 5200 protons for every iron nucleus, the dose deposited in the BFO by iron nuclei is still about 1/20<sup>th</sup> of the total dose from the protons because each iron nucleus deposits 676 times the amount of energy that a proton deposits. Moreover, the dense track of ionizations left by the heavy particle is more effective in producing biological damage than is the proton. Just how much more effective is still controversial. Nonetheless, current radiological health practice assigns a quality factor (Q) of twenty to all heavy ions which means that a dose (in Gy) of heavy ions such as iron is considered to be 20 times more effective in producing cancer than is the same dose of x-rays or energetic protons. This difference in effectiveness is taken into account by the use of a quantity called the dose-equivalent with units of sievert (Sv). (One Sv is equivalent to 100 rem.)

The annual BFO dose-equivalent to an EVA-suited or other thinly shielded individual on the lunar surface is about 0.15 Sv (15 rem). This dose-equivalent includes both the primary GCR and secondary particles such as neutrons produced in the astronaut's bodies by the fragmentation of primary heavy ions or of nuclei hit by primary particles.

Shielding by 1.5 cm of aluminum (4 g/cm<sup>2</sup>) reduces the BFO dose-equivalent by only 13%. Ten cm of aluminum (27g/cm<sup>2</sup>) reduces it by about 30%. After this shielding thickness, most heavy ions have broken up and the dose and dose-equivalent are dominated by secondaries. Neutron secondaries, being uncharged, can penetrate much further through matter. Therefore, if burial of a lunar base is a shielding option, about 2 meters of lunar regolith may be required to reduce the dose-equivalent to optimal levels.

Periodic solar particle event radiation may be much more intense than GCR, but it is less penetrating. Adequate shielding against GCR (e.g., 2 meters of lunar regolith) will also provide protection against even anomalously large SPE such as occurred in August 1972. SPE warning systems will be required so that thinly shielded individuals can seek shelter.

## Construction of Concrete Lunar Structures

HARUYUKI NANBA, YOSHIO KAI

KUNIHICO SUGIHARA, SHINJI MATSUMOTO

TETSUJI YOSHIDA, TOMOHIRO OSAWA

A proposal is made regarding construction methods of concrete habitation structures on the lunar surface. This study is carried out on the premise that a concrete plant using lunar resources has already been operated on the moon and precast concrete components are manufactured there.

A lunar habitation structure will be maintained an inner pressure of approximately one atmosphere. Since the outside is a vacuum, the inner pressure will cause significant stress on the structure. The larger the structure, the greater will be this stress. It will thus be difficult to realize rooms with large open spaces unsupported by columns. Accordingly, the best type of structure for lunar habitation is an aggregate of small compartments. These compartments should be hexagonal in shape, and will result in great layout flexibility.

If larger rooms are build, columns should be used to reduce the stress on the roof structure. These columns can form a triangular grid, giving high artistic flexibility.

Lunar structures must protect their occupants from harmful radiation in space. Two approaches are conceivable here.

One is to construct structures underground, so that they will be shielded from radiation naturally by the lunar surface soil (regolith). Underground structures should be cylindrical cavities, but without too great a diameter, since otherwise the stress at the foundation will be unduly large. The other approach is to construct dwellings above ground and coat them with regolith to block radiation.

Practical design concepts, then, for constructing a lunar habitation structures built above ground made up of hexagonal structures, and underground structures that are cylindrical in shape. These concepts resemble earth's realm of nature, where bees construct hexagonal hives and ants live underground in cylindrical cavities.

The authors proposed a prototype structure on the basis of the concept mentioned above, carried out the structural design, and made construction planning.

# APPLICATION OF LOW-TEMPERATURE PLASMA REACTORS AS A RESOURCE MANAGEMENT SUBSYSTEM IN CLOSED-LOOP PROCESSING APPLICATIONS

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As the exploration of space continues and Lunar and Martian bases are developed, new challenges resulting from the extraterrestrial environment will require the development of more comprehensive Environment Control/Life Support Systems (ECLSS). For larger systems, such as bases, the scope of the ECLSS will need to expand beyond life support to include manufacturing and the processing of wastes and materials. A successful ECLSS will consist of a closed-loop processing (CLP) resource management system. Figure #1 illustrates the interaction between each group within the CLP system. For such a system to be successful in a lunar or martian environment, technological advances must take place in the areas of reaction engineering, reaction control, and processing techniques. To meet these challenges, the Advanced Technologies Group of the University of North Dakota Energy and Mineral Research Center (ATG) is performing research into the use of low-temperature plasma reactors as the cornerstone of such a system.

The first phase of the ongoing ATG low-temperature plasma research program deals primarily with the conversion of biological wastes to recyclable products for use elsewhere in a CLP system. A low-temperature reaction scheme was chosen to convert the organic material in a waste stream to a gas, primarily  $\text{CO}_2$ , while leaving the inorganic components unchanged. Reaction specificity, reaction rate control, and rapid reactor and reaction shutdown are characteristics which contribute to the safety and usefulness of this system. During experimental testing, five materials were processed: a sunflower, an oat plant, soybean plant, and a plastic bag. The low-temperature oxygen plasma was produced by ionization using a high-frequency induction coil and subsequently passed over the waste material to oxidize it.

In each case, over 98% of the organic material was removed from the feed stream. A preliminary size and electrical design of a combustor was made based on the conversion and residence time data obtained during the test program. The proposed reactor consists of a 4.3 ft<sup>3</sup> rotating fluidized bed requiring 280.3 kw-hr/lb of feed material. This reactor system would provide waste disposal for a crew of eight. The size and power requirements are similar to other proposed processes as reported by Slavin et al (1).

The effectiveness, safety, and ease of operation of low-temperature plasma reactors offer a processing alternative for the recycle and recovery of waste materials. The prospect of using this type of reactor system, which is capable of utilizing both reductive and oxidative atmospheres, opens the door to the use of the system for waste management, the production of hydrazine from ammonia, and processing of lunar and martian soils by reduction. Because of the potential flexibility for the use of a oxidative or reductive plasma reactor, the low-temperature plasma reaction system could be a key subsystem in a CLP system.

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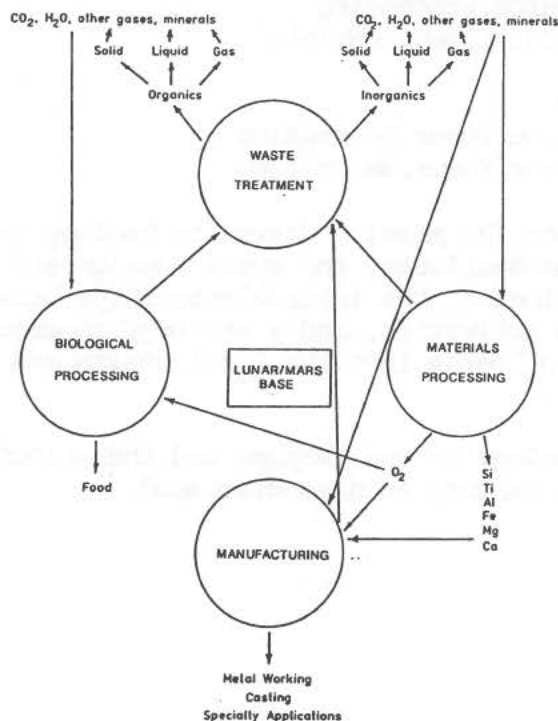


Figure 1. Closed-Loop Processing (CLP) Resource Management System

## TECHNOLOGIES FOR SPACE EXPLORATION IN THE 21st CENTURY

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Exploration of the Moon and planets present significant engineering challenges to the system designers and leads inevitably to a requirement for new technologies. The objective of this paper is to summarize the Agency's evolving technology program and the relationship of this program to the definition of the exploration missions. A topical summary of technologies currently considered critical to the exploration missions follow:

HUMANS IN SPACE

- EVA/Suits
- Human Performance
- Space Adaptation
- Life Support

TRANSPORTATION

- Terminal Landing Hazard Avoidance
- Autonomous Rendezvous and Docking
- Aerobraking
- Propulsion
- Cryogenic Fluid Management

EXPLORATION

- Planetary Rover
- In-space Assembly and Construction
- Surface Sample Acquisition, Analysis, and Preservation
- Resource Processing
- Optical Communications

POWER

- Surface Power Generation
- Nuclear Power Generation

The paper discusses the mission driven technology requirements, the technology options available, the system design and performance impact of the new technologies, the interrelationships between the technology and system definition activities, and a strategy to ensure the effective transfer of these technologies into the final design and development of the selected missions.

The role of technology in the shaping and the selection of the mission(s) to begin the 21st Century is also discussed.

A SEISMIC RISK FOR THE LUNAR BASE; J. Oberst and Y. Nakamura, The University of Texas, Institute for Geophysics and Department of Geological Sciences, Austin, TX 78712.

**Introduction.** Contrary to the common belief of the pre-Apollo era, the Moon is by no means a seismically "dead" planet. This has become obvious during the operational period (1969-1977) of the Apollo Seismic Station Network (1,2). More than twelve thousand seismic events were detected by the long-period seismographs. Although most of them represent weak, tidally induced moonquakes (body wave magnitude  $m_B < 3$ ) deep in the lunar mantle (2), some of the strongest events ( $m_B$  up to 5.5), believed to be of tectonic origin, occur at shallow depths (3,4,5). These shallow moonquakes may pose a substantial risk to the operation of the lunar base.

**Occurrence Rate of Shallow Moonquakes.** Based on the 28 events identified as shallow moonquakes during the entire operational period of the seismic station network and assuming that these events occur randomly distributed in space and time we estimate the occurrence rate of these events (see Figure 1) as  $\log N = -0.8 m_B + 2.7$ , where  $N$  is the cumulative number of shallow seismic events having body wave magnitudes greater than  $m_B$  occurring within an area of  $10^6 \text{ km}^2$  per year. We thus estimate that the chances for the lunar base to experience a shallow moonquake of e.g.  $m_B > 4$  within a range of 50 km are one in 600 years. A comparison with the distribution of terrestrial intraplate seismicity data shows that lunar seismicity is very similar to the approximate average seismicity of the Central United States (6). However, it is noted that the potentially damaging effect of seismic events of equivalent magnitude at equal range may be different on the moon compared to Earth because of the differing properties of seismic energy transmission.

**Open Questions.** Before establishing more reliable risk estimates two questions need to be answered: (a) how close to the surface do shallow moonquakes occur and (b) how are they distributed spatially. The focal depths of these events are important parameters for estimates of their potentially damaging effect on the lunar base. In order to determine these focal depths, however, observational data of shallow moonquakes occurring at close range are needed. So far, all shallow moonquakes were observed from teleseismic distances  $> 500 \text{ km}$ . Identifying a non-random spatial pattern of the shallow moonquakes is important because there may be regions of increased seismic activity, where a seismic risk is possibly much higher than what the above average estimate indicates. Because of the small number of events observed, identification of such a pattern is difficult at present. Are they associated with topographic features such as young thrust faults (7)? Do they occur in preferred geologic settings such as the mare basins (3,4)? Avoiding such regions of perhaps greatly increased seismic activity may significantly reduce the seismic risk for the lunar base.

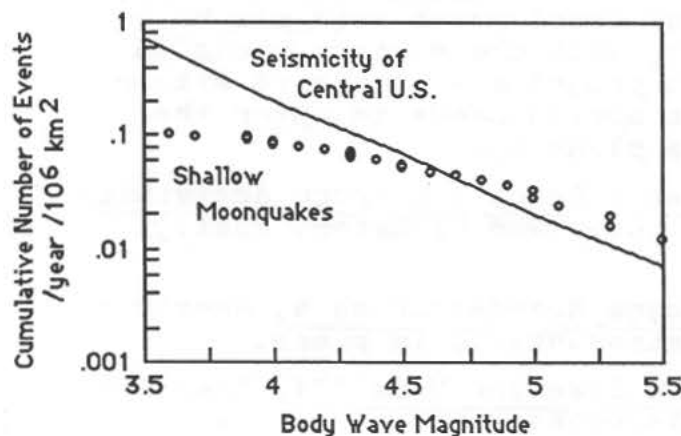


Fig.1: Magnitude-Frequency Relations for Shallow Moonquakes and Earthquakes

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LOW-COST DELIVERY OF WATER FROM PHOBOS/DEIMOS TO THE MOON, Brian O'Leary, Future Focus, 5136 E. Karen Dr., Scottsdale, AZ 85254.

Every two years, the moons of Mars are more accessible to Earth in terms of delta-v than any known natural object. Also, they are likely to contain significant quantities of easily extractable water, evidence which will be verified on the 1988/89 Soviet Phobos mission. These data, plus interest in Mars missions, provide strong rationales for using Phobos and Deimos as centers for propellant processing and Mars exploration.

A 1987 study for the NASA Marshall Space Flight Center, and presented at recent conferences<sup>2,3</sup>, shows that a nine-year, four-mission program involving the extraction of water and propellants from the Martian moons could deliver ~10,000 metric tons of water to low Earth orbit, the Moon, and Mars. This large resource, economically obtained, could make possible the establishment of lunar and Mars bases on shorter time-scales than most projections made to date. This program might utilize the external tank as a launch vehicle, as a cryogenic storage facility in LEO and Phobos/Deimos, and as an inter-planetary and cislunar transfer vehicle.

This paper presents strategies for establishing a lunar base using Phobos/Deimos water for propellants and for life support on the lunar surface. The favorable economics of water and/or hydrogen delivery from the Martian moons (versus from Earth) to lunar orbit and to the lunar surface, already established in parametric studies<sup>4</sup>, when combined with the four-mission program scenario, would provide enough infrastructure to construct mass-drivers and a rapidly growing lunar base as early as 2005. Scenarios, schedules, weights, production throughputs, and requirements are presented.

One result is that the fastest path toward creating economical lunar operations and bootstrapping toward large-scale space industrialization will include the input of resources from Phobos and Deimos. I suggest that manned lunar and Mars exploration and development need not be in competition. On the contrary, with the Martian moons as early propellant depots, both programs will thrive within a few years of start-up. This option needs to enter the mainstream of NASA long-range planning.

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Radiation Shielding to Solar Power Satellites:  
Results of the January 1988 SSI/Princeton Lunar Systems Study

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In his October 1987 speech to the IAF, NASA administrator Dr. James Fletcher predicted the construction of solar power satellites and large human habitats in space from materials mined on the lunar surface. During the 1970s and early 1980s, NASA (References 1 & 2) and the Space Studies Institute (Refs. 3 & 4) conducted a number of systems studies on the subject of lunar materials for space export and construction. The reports of the National Commission on Space and Dr. Sally Ride recommend the construction of human outposts on the Moon and the use of lunar resources for space construction and industry.

During the week of January 11, 1988 a team of 20 aerospace engineers and scientists, under the direction of Dr. Gerard K. O'Neill, Dr. Peter E. Glaser, Mr. Edward Bock, and Mr. Gordon Woodcock will meet to examine the steps required to return to the lunar surface and use locally available materials and energy on the surface and throughout cislunar space. An examination of the output products of such a cislunar infrastructure ranging from raw soil for radiation shielding to solar power satellites for terrestrial energy production will be undertaken. The study will identify in particular those products and services which have a near-term pay back. In addition, those areas of technology which need to be developed before such enterprises can commence will be identified.

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HMF MEDICAL DECISION SUPPORT SYSTEM -  
EXTENSIONS FOR LUNAR BASE

D. V. Ostler  
Krug International

Establishing a Lunar Base will add some significant new requirements to the Computerized Medical Decision Support System (MDSS) now being planned for the Space Station.

The lack of emergency return capability will require the MDSS to be expanded to meet the needs of a physician practicing medicine with only delayed access to ground based medical consultants. On-line retrieval of the most current medical literature will be provided as well as the continuing medical education training materials necessary to have the Lunar Base medical officer maintain his medical skills. The MDSS will also provide protocols and on-line training for the extended surgical procedures that are not possible in Space Station's zero gravity, but that will be possible with the one-sixth gravity on the Lunar Base. The MDSS will provide new medical diagnostic and treatment protocols based on the space physiology research accomplished during the Space Station era.

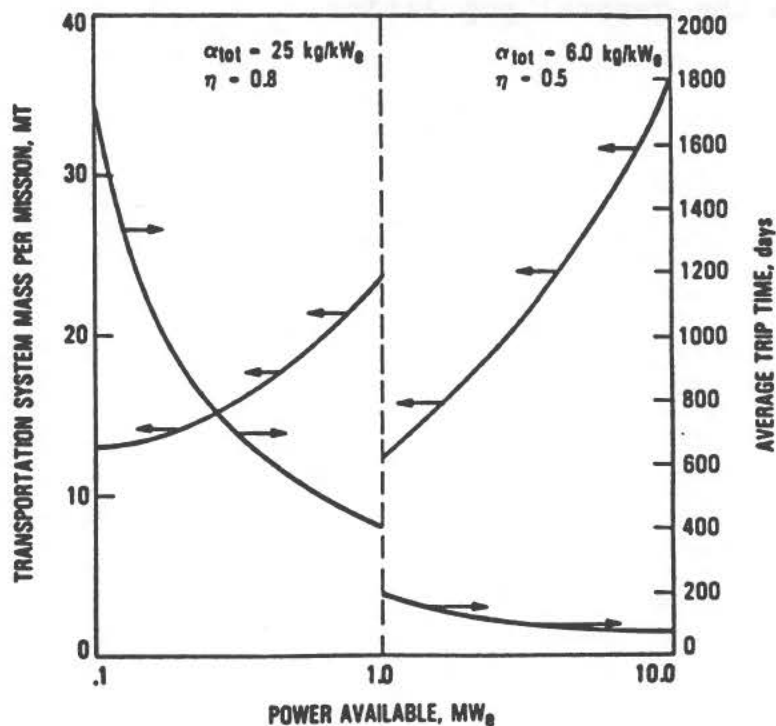
In addition, the Lunar Base will surely involve larger crew sizes than the Space Station and multiple patient care will need to be supported by the MDSS. The Information Bus (MIB) presently incorporated in the Space Station Health Maintenance Facility will allow instrumentation used by the medical officer to be integrated into a single database and displayed automatically. This will allow the medical officer to provide physician and nursing care to multiple patients. The MIB will also allow widely used clinically validated closed loop instrumentation control algorithms to be used to reduce the workload of the medical officer in providing therapy.

ELECTRIC PROPULSION FOR LUNAR EXPLORATION AND LUNAR BASE DEVELOPMENT;  
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In the development of the Lunar Base and the precursor exploration of the lunar surface, the transportation of large masses to lunar orbit will be essential. Electric propulsion can significantly reduce the launch mass-to-orbit in support of these explorations and permanent settlements.

Analyses of the benefits of both solar-electric and nuclear-electric propulsion are presented. Detailed designs of the Orbital Transfer Vehicles (OTVs) and their on-orbit support facilities are described. The NASA Marshall Space Flight Center Revision-9 mission model for lunar exploration was analyzed. The propulsion requirements for chemical and electric propulsion missions are compared. Lunar landing-and-return module designs are also provided.

Using nuclear-electric propulsion, the benefits of the reduced launch mass for the long-term resupply of the lunar base are significant: for a chemical-propulsion mission from Low Earth Orbit (LEO) to Low Lunar Orbit (LLO), the total transportation system mass per flight is 75000 kg. Using a 1-MW<sub>e</sub> nuclear-electric propulsion OTV, the total transportation system mass savings per flight is up to 60000 kg.



The Effect of Power Level on the Average Total Transportation System Mass per Mission and the Average Mission Trip Time Required for the Completion of the Lunar Base Construction Mission

DISTRIBUTION OF HUMAN WASTE SAMPLES IN RELATION TO SIZING WASTE PROCESSING IN SPACE; D. B. Parker, and S. K. Gallagher; Space Studies, University of North Dakota, Grand Forks, ND; and USDA Human Nutrition Research Center, Grand Forks, ND

Examination of more than 25,000 days of human waste production from 171 individuals permitted estimates of the size of waste processing facilities needed for small Closed Ecological Life Support Systems. The data shows the wide range and large skewness of values for waste generation, with the mode substantially below the mean. This implies that design for the extreme values would usually be over designing and use of the mean will be under designing. The impact an individual with extreme values has on equipment size requirements decreases as crew size increases. Curves are presented which show size required to handle crews of 1 to 20 individuals including the percentiles of the population which can be handled as equipment size decreases. Recommended daily handling capacity for a crew of 8 is 32.5 liters for urine, 1.9 kg for wet stools, and 375 gm for dry stool material. Some recent design studies have used urine volumes which would handle less than half of crews selected from the population sample our data represents. As less rigorous selection standards are applied to individuals going into space, waste handling equipment capacity needs to be designed to reflect the greater variation in waste production which exist in the general population.



## BUILDING TECHNOLOGY FOR EXTRATERRESTRIAL APPLICATION

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Extraterrestrial building will require the development of a new building technology. The application of this technology in extraterrestrial environments will embody a new architecture. This architecture will be characterized by its performance oriented design criteria as opposed to the predominate cosmetically oriented design criteria of the conventional earth-bound building arts. The technology required to drive this architecture is currently being developed and applied, primarily by private industry, in response to some specialized requirements of today's building community. This technology is typically referred to as "space frame" technology and is embodied to varying degrees in several existing space frame systems.

Principles derived from a natural-structure ethic will govern the design criteria of extraterrestrial architecture. Space frame technology is rooted in the study of natural form. Space frame technology will combine unparalleled structural performance with highly adaptive configuration geometries to provide unprecedented design and engineering flexibility for extraterrestrial application. The result will be an entire new vocabulary of form language for the architect, a vocabulary of form generation that will ultimately even revolutionize conventional earth-bound architecture.

The foundation of this emerging architectural technology is found in the principles of configuration iteration through the manipulation of fundamental spatial elements. This form giving strategy is transformed into a practical design tool by means of sophisticated computer technology. Computer aided design will be essential, but not in the sense of trade show demonstrations imitating drafting. Computer aided design will mean the sophisticated manipulation of a kit of parts or recipes, unit cells, basic spatial units or modules to generate overall architectural design. Much work remains to be completed in the development of these software systems.

Space frame technology is highly responsive to the infinite range of demanding structure performance considerations that will be encountered in building off the earth's surface. These diverse considerations include; material properties and performance requirements, structure surface to volume ratio, global and local stress distribution, minimum component type inventory, integration of various structure interface systems (glazing and cladding, louvers, mechanical, electrical, HVAC, panels, etc.), assembly strategies, and the impact of planetary-solar geometry on proposed configurations. An extremely refined level of performance optimization is attainable through the use of space frame technology.

A significant prototype for the application of this new technology and the development of this new architecture is currently underway in the southern Arizona desert. It is perhaps the most exciting scientific and architectural project of the Twentieth Century. A glass sealed space frame structure will enclose 5 million cubic feet of space and cover 2.5 acres of varied terrain. A self-sustaining tropical environment will be "planted" within the space frame envelope. A selection of plant and animal species along with eight people will be sealed inside the structure for an initial two year experiment. The project is called Biosphere II, named after our own Earth, Biosphere I, and is intended to function as a prototype environmental package for application in future space colonization; a self-sufficient, self-perpetuating and self-contained ecosystem. Pearce Structures is responsible for the design, engineering, manufacturing and installation of the space frame structure. The space frame technology developed and employed by the company responded to efficiently solve a wide range of unusual and demanding problems particular to this project.

The technology required for extraterrestrial architecture is emerging from the marriage of the technology and techniques of the information age with structural systems rooted in a tradition of natural form. Space frame provides the syntax, allowing for sophisticated manipulation and synthesis of the basic elements of the vocabulary. Structural form will derive from the interface between the designer and the automated system incorporating the vocabulary of space frame technology, and be determined by the context in which the system is operative (i.e. orbital, Lunar surface, Martian surface, etc.). This process unlocks a rich new architectural frontier, extremely promising and largely unexplored. The resulting structural solutions will represent the indigenous architecture of a technologically advanced, resource lean, performance oriented extraterrestrial culture.

COMPUTER PROGRAM FOR PRELIMINARY SIZING OF LUNAR  
VEHICLES; A.J. Petro, NASA Johnson Space Center

One of the most important supporting elements for a lunar base program is a system of vehicles for transporting people and cargo between low Earth orbit and the surface of the Moon. This paper will describe a FORTRAN program which was developed to calculate the size and mass of multi-stage vehicles for lunar transportation. The required propellant mass is computed using a form of the rocket equation which also takes into account the mass of propellant tanks, vehicle structure, and other systems. Based on the mass computation, it is possible to estimate propellant tank dimensions and define an overall vehicle configuration.

The program is designed to allow the user to define the number of rocket stages to be used for one-way and round trip lunar missions and the amount of payload to be carried on each leg of the trip. Also, any type of propellant combination can be specified and the return to Earth orbit can be accomplished with the aid of aerobraking or using propulsion alone.

The program provides a quick method for estimating vehicle sizes and performing trade studies with a range of vehicle and trajectory options. The application of this program in trade studies and the definition of a baseline lunar transportation system will be described. A more general application of the program to interplanetary vehicle sizing will also be discussed.

OPERATIONAL CONSIDERATIONS FOR LUNAR TRANSPORTATION;  
A.J. Petro, NASA Johnson Space Center

Transportation of people and cargo between low Earth orbit and the surface of the Moon will be one of the most important elements in a lunar base program. This paper will identify some of the operational issues involved in lunar transportation and recommend approaches to account for operational requirements in the early stages of lunar base development.

Because transportation operations will be a major cost factor in the program, the vehicles must be designed for efficient operation and low life cycle cost. The Space Shuttle program had similar goals at its inception and so the lessons of Shuttle operations provide a good experience base for development of operations concepts for routine lunar transportation. For example, the challenge of maintaining a high flight rate with a first-generation reusable vehicle indicates the need to develop, fully test, and possibly modify vehicles prior to their use in support of an operational lunar base.

Operational considerations to be discussed in this paper include flight planning, flight safety, crew training, mission control, and vehicle servicing. Human factors such as radiation exposure, habitability, crew workload, and physiological adaptation should be considered early in the vehicle design process. Likewise, constraints due to orbital mechanics such as launch windows and lighting at landing sites must be considered in evaluating trajectory options.

### UNIT OPERATIONS FOR GAS-LIQUID MASS TRANSFER IN A REDUCED GRAVITY ENVIRONMENT

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Materials processing operations and ecosystem management on lunar bases will require a variety of gas-liquid contacting devices. However, the reduced gravity environment of a lunar base or a space station will complicate conventional processes involving mass transfer between gases and liquids. Standard Earth-based unit operations utilize gravitational forces to separate gas and liquid phases and may be ineffective in reduced gravity.

The approach to gas-liquid contacting in low gravity will use rotating columns which do not disperse the fluids as bubbles or drops but maintains a thin liquid film moving along the column wall and the gas phase flowing in the center. This allows mass transfer between the gas phase and the liquid film moving in co-current or counter-current flow. The rotating column forces the liquid film to flow against the gravity gradient by having an expanding conical shape which results in a force component that can oppose gravity. Scaling rules show that as the gravity is reduced, the conical angle decreases. Scaling criteria based on maintaining film thickness consistent with Earth-based correlations of data appear to be the best choice for designing such operations in the absence of data taken in the reduced gravity environment. The main disadvantage of phase contacting by a moving film as compared to the usual dispersion of bubbles and drops is a lower overall mass transfer rate which requires larger machinery to handle a given feed rate.

SCENARIOS FOR MAN-TENDED LUNAR OPERATIONS; Paul G. Phillips, Eagle Technical Services, Inc., 711 Bay Area Blvd., Suite 613, Webster, Texas 77598.

Human sorties and temporarily-occupied lunar facilities will be required prior to establishment of a permanently-staffed lunar base. An understanding of the options and constraints for these missions must be developed now so adequate near-term program planning may be done.

The basic approach is to develop a logic network linking several scenarios, each based on a different principle base function. Each scenario begins with a predefined robotic exploration scenario and assumed general results of that exploration. The major functions include life sciences and interplanetary mission precursor activities, lunar sciences, astronomical sciences, and wet and dry lunar resource exploitation. Trade studies and analyses are used to develop and define required primary activities and supporting capabilities and facilities for each scenario. Scenarios are linked by common support requirements and each scenario is completed by definition of its ancillary functional capabilities.

Several scenarios are identified in the logic network for the major base functions. Requirements, capabilities and milestones are identified as common or unique and as dependent on or independent of the robotic precursors. The final scenario of choice will depend on results of current in-depth strategy development, the near-term political and economic realities surrounding the space program and the lunar base, and at the beginning of lunar development, the results of robotic exploration.



LUNAR BASE LAUNCH AND LANDING FACILITIES; Paul G. Phillips, Eagle Technical Services, Inc., 711 Bay Area Blvd., Suite 613, Webster, Texas 77598. Charles H. Simonds and William R. Stump, Eagle Engineering, Inc., 711 Bay Area Blvd., Suite 315, Webster, Texas 77598.

Lunar base launch and landing facilities have generally been treated as secondary facilities or ignored completely. This study was performed to characterize them and verify that none of the resultant requirements are primary drivers of the lunar base itself.

The nature and scale, as well as the growth of lunar landing and launch facilities, are found to depend very heavily on the base development scenario. Facility growth has three basic stages of development covering early lunar base setup, lunar base growth, and sustaining operations. The timing of the transitions between these stages depends on the major emphasis of the base. Permanent prepared facilities are generally not required until lunar resources are exported or vehicles must be fueled on the surface.

Various factors, including navigation requirements, visibility, blast effects and vehicle landing ellipses are considered in defining surface characteristics and pad locations and sizes. Concept definitions and options are presented for some facilities required during permanent sustaining operations. Permanent facilities may include: cryogenic liquids storage and processing, lunar solids storage and processing, launch vehicle fueling, launch vehicle maintenance, launch platforms, and navigation aids.

A PHASED APPROACH TO LUNAR BASED AGRICULTURE; Tom Polette and Larry Toups, SICA, College of Architecture, University of Houston, Houston, TX 77004

The ability to grow abundant quantities of nutritious plant materials on the Moon will be an important factor in achieving an ultimate goal of self-sufficiency. This paper discusses considerations, requirements, concepts, and a possible staging scenario for three in-situ lunar agricultural development phases:

- 1) Plant experiment and test facilities to demonstrate the feasibility of lunar agriculture;
- 2) Pilot facilities to demonstrate processes, yields, and nutritional benefits of lunar agriculture;
- 3) Production facilities scaled to provide a significant variety and quantity of food materials at an advanced stage of lunar development.

Priorities and concepts addressing these phases include plant growth, utilizing hydroponic techniques and lunar soil substrates; automation and robotic systems, minimizing manpower requirements for plant growth and harvesting; and facilities to provide environments with controlled atmospheres, lighting, temperature, and radiation protection.

# SEARCH FOR ORGANIC MATTER ON THE SURFACE OF THE MOON

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University of Maryland, College Park, Maryland and  
Ed Hare, Carnegie Geophysical Laboratory, Washington, D.C.

In the study of exobiology we are interested in the path by which organic molecules may have been formed during the early stages of the solar system. The exhaustive study of the Apollo samples demonstrated the presence of traces of hydrocarbons. The evidence for the other molecules of biological importance was not conclusive. The establishment of a laboratory on the moon will provide a unique opportunity for the analysis of organic compounds which may have been contributed by carbonaceous chondrites which are known sources of organic matter. An analytical laboratory with special emphasis on GC-MS will have to be constructed on the moon. Since the only prebiotic material available for our studies is the organic matter in carbonaceous chondrites, these continued studies on the lunar surface will provide important clues to the understanding of the origin and evolution of life on earth.

**AUTOMATED BIOMEDICAL RESEARCH PROJECT  
(BmRP)  
PLANNING SYSTEM**

**by**

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NASA Johnson Space Center, Houston, Texas 77058

R. Michaud, L. Neal Jackson, M. Singletary, N. Wilson,  
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77058

The long range planning required to support the Life Sciences mission onboard the Space Station is one of the many challenges to the science and engineering community preparing for long term space science activities. In the past, opportunities for life sciences research have been limited by very short duration STS missions which have inherently short periods of operation. Planning for these missions is an intense and complicated effort which encompasses complex experiment protocols, equipment, materials and crewtime resources to support a myriad of life sciences disciplines. However, with the Space Station and its laboratories of complex supporting equipment, the long range planning to support 90, 180, 270 or possibly 360 day mission sets must be accomplished with the same proficiency and intensity as any STS one week mission. To assist the advance planning and program development required for this complicated on-going task, an Automated Life Sciences Planning System is being developed. This planning system will increase Life Sciences responsiveness and adaptability to changing Space Station and STS operational, logistical, manifest and budget constraints. The system consists of two major expert subsystems which use a common Biomedical Research Project (BmRP) Life Science Database. This database contains in-depth information on experiment protocols, equipment, procedures, resources and hardware development schedules for each science discipline. The first major expert subsystem is the Automated Reference Mission Operational Analysis Document (RMOAD). The Automated RMOAD is capable of generating Reference Mission Operational Scenarios (RMOS) based on variable mission operational guidelines and constraints e.g. volume, power, mass, etc. selected for the BmRP Life Sciences payload(s)/payload element(s) to be flown as a particular mission set for selected durations. The Automated RMOAD serves as the definition phase for the reference payload(s)/payload element(s) development and provides detailed supporting data required for onboard experiment, procedures, hardware, resources, and logistics. The second major expert subsystem is the Automated Budget and Cost Estimation System (ABACES). The objective of this subsystem is to develop operational and cost efficiency for Life Sciences through standardized budget presentations, reduce the manpower required to support budget planning exercises, and standardize budget analysis procedures and hardware costing methodology and requirements. The system can use a RMOS for a particular mission set and generate a bottoms-up costing for the mission with supporting hardware development schedules. Missions can also be constrained by a budget for a selected mission duration. The ABACES will generate a top-down Reference Cost Analysis Scenario (RCOS) based on hardware complexity, historical cost data, and operational constraints for a mission set which will satisfy all budget constraints and provide supporting hardware development schedules. This dual costing/ budgeting and reference mission operational scenario development capability is paramount to the success of long range planning to compensate for funding changes in the current fiscal environment.

## **LIFE SCIENCES SPACE STATION SPACE BIOLOGY PROJECT PLANNING**

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The Life Sciences Space Biology (LSSB) Project is a major element of the Life Sciences Space Station Program. The majority of the LSSB research will be performed within the United States pressurized laboratory module and will focus on understanding the influence of microgravity on humans, animals, and plants. The LSSB Project is composed of four types of research. The first is Gravitational Biology - research to understand how gravity is sensed and how it affects reproduction and development. Space Physiology research is basic biology studies on appropriate test subjects to (a) evaluate the effects of the microgravity environment and (b) elucidate response mechanisms including the time course of the adaptation / de-adaptation process. The third area is the development of Closed Ecological Life Support Systems (CELSS) Prototypes and the assessment of the productivity and growth of plants and algae in space, and technologies to support future CELSS subsystems. Exobiology research will study of the evolution of biogenic components. The NASA Johnson Space Center LSSB Project is active in each of these research areas with special emphasis on Space Physiology research with humans and human models. The JSC LSSB Project will be a significant factor in developing data to determine: the potential effects to crew and other live beings during long duration stays in microgravity and the life support systems needed for interplanetary travel. The types of research that will be performed within the LSSB Project will demand the development of new technology spinoffs. As the Space Station Program evolves, the potential of the LSSB Project will expand to include research for determining the feasibility of man's participation in lunar bases, interplanetary travel, and exploration of the universal frontier.



ENGINEERING VERIFICATION OF THE BIOMASS PRODUCTION CHAMBER;  
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The central focus of the John F. Kennedy Space Center Breadboard Project for NASA's Controlled Ecological Life Support System (CELSS) Program is an atmospherically sealed steel cylindrical chamber (8m high x 3.5m diameter), modified for plant growth studies. The objective of the CELSS Breadboard Project is to develop a prototype bioregenerative life support system and conduct evaluation tests sufficient to determine mass and energy fluxes through, and budgets for, the system. The BPC is the first of three CELSS modules developed. Waste management and food processing will be integrated with the BPC. This paper discusses the importance of this facility to the CELSS Breadboard Project and ultimately to the development of permanent human-tended bioregenerative space modules such as for a lunar base.

The most unique element of this chamber facility is its sealed atmospheric condition. Tests conducted during this engineering test to establish the leak rate for the BPC included evaluations involving pressure and trace gas injection. The leak rate of the chamber indicated that it would be useful in addressing gas contaminate problems that may develop in the operation of the biomass production facility. The establishment of this chamber as a functioning test facility is a major milestone in the development of a CELSS for future long-duration spaceflight.

**THE LUNAR ORBITAL PROSPECTOR (LOP)**

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Detailed remote sensing of the lunar surface is both a necessary precursor to the establishment of lunar colonies, and an essential support to the proliferation of such colonies and the exploration missions emanating from within their borders. While there is much discussion of human and robotic exploration of the lunar surface, such exploration is necessarily limited to some proximate distance from the support base. Real time, high resolution, global characterization of the lunar surface by a constellation of complementary orbital sensors will greatly aid in understanding the moon's geophysical structure and locating exploitable minerals and raw material deposits.

This paper presents a detailed description of a lunar launched and recovered orbital sensing system with the primary mission of "prospecting" the moon in support of early lunar colonization and exploitation efforts. It is envisioned that such a system will consist of several satellites in different orbits with modular sensor packages. The satellites will be launched into orbit using lunar derived propellants to avoid the energy penalties associated with earth launched systems. The ability to land and recover the modular instrument packages allows their reuse in different configurations as well as possible use for remote surface exploration. The above characteristics, coupled with the abilities to change orbital parameters, scan locations of interest and supply a near real time data return, provide a considerable degree of system responsiveness.

The paper discusses specific mineral/raw material spectral emission properties and the associated sensor sensitivity and resolution requirements. It then explores candidate sensor concepts and postulates a modular sensor package design. Launch and orbital platform requirements are discussed with emphasis on the use of vehicles using lunar propellants. The paper then addresses methods for changing orbital parameters in order to change surface coverage and/or sensor dwell time. Sensor, launch/recovery, orbital tailoring and energy requirements are then combined into a candidate design for the lunar launched and recovered system. The paper concludes with an assessment of the value of constellations of complementary instrument packages, data storage and transmission requirements and an overall system assessment.

\* Associate Fellow, AIAA; Professor, Mechanical Engineering.

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**BIOSENSORS FOR LIFE SUPPORT SYSTEM MONITORING**

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Lunar habitats will likely incorporate large partially closed life support systems that will house a broad spectrum of living organisms. In addition to the production of unspecified organic compounds by a variety of living organisms, interaction with lunar materials may also result in significant production of organo-metallics. Routine physico-chemical air and water regeneration will likely cope with many hazardous or obnoxious compounds. However there will be an acute requirement for broad spectrum biohazard monitoring systems sensitive to a wide concentration range of unspecified organics, metallo-organics, pyrolysis products etc.

Available sensors that can provide adequate selectivity, sensitivity or response-time are large, complex and expensive.

Recent advances in biosensor technology may provide light weight economical monitoring devices. A number of research groups are working in this field worldwide, and practical devices are starting to emerge.

Canpolar is currently developing a rugged liquid phase sensor applicable to food processing applications such as quality assessment. The specific compounds to be sensed will depend on the application. To date our work has focused on development of a rugged, re-usable probe with a response time of less than one second.

Research work in this field over the next few years will likely lead to a variety of biosensor devices for gas and liquid phase measurement. Broad spectrum biohazard sensors appear to be possible in principle. Fundamental problems still exist in stability and calibration of sensors. However, this technology will likely be one of the tools available to designers of space facilities in the 21st century.


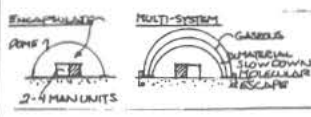
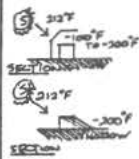
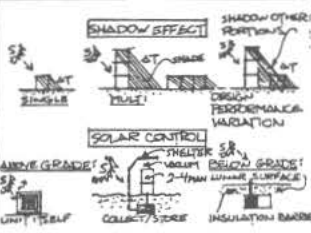


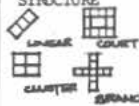
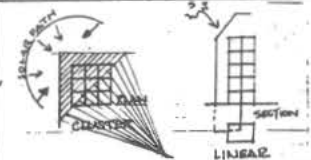
# PRELIMINARY DESIGN STUDY OF LUNAR HOUSING CONFIGURATIONS

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A preliminary design study assesses various configurations for habitation of the lunar surface. The configurations vary from a four-man initial habitation concept to a forty-eight-man larger scale concept.

The analysis is based on a design model categorizing the essential conditions for occupancy. The design model is built to present each configuration in light of certain issues. Some of the major issues include potential materials, construction options, occupant type, human existence issues, design issues and lunar environmental conditions (ie solar intensity, diverse temperature flux).

The model presents the attributes, potentials, particular requirements necessary, the advantages and disadvantages of each configuration. It further identifies the areas that need solutions, future investigation, potential problems, scientific advancement or innovation in order to implement. A portion of the design model is portrayed below. Excerpts of the configuration matrix are included for illustration.

TOPICS	CONDITIONS	STATEMENT AND OBJECTIVES	CONFIGURATIONS
<b>ATMOSPHERE</b> 	-no appreciable atmosphere -vacuum-like environment -exosphere at surface -traces of elements -light molecules escape -extreme temperature flux -no solar radiation barrier	-provide artificial atmosphere that is fault tolerant -provide equivalent to earth's 120 mile atmosphere -design with advantages of vacuums exploration: materials, system	
<b>SOLAR INTENSITY</b> 	-lunar day = 14 earth days -lunar night = 14 earth days temperature flux: 212°F to 312°F -same intensity of temp. variation in shaded areas -vacuum allows for some energy slowdown -no heterosphere for solar radiation blockage	-control impact of solar radiation on occupied areas -control temp. flux by physical systems design -construct using vacuum conditions -develop shelter to withstand severe cold vs severe heat (ie block solar radiation affect) -collect solar radiation: store re-use as heating supplement for occupied areas -work with solar path, angles, shadow phenomena to advantage	
<b>OPTIMUM FORM</b> 	-hostile environmental condition -provide maximum living space, minimum area/volume -ease of movement: see circulation -security/life safety parameters: see section for details	-determine ratios for vol./sq.ft./surface area -minimize potential failure: nodes, skin, lines -minimize exposure of nodes, lines -minimize surface failure tendency -research beyond scope of paper -requires additional study by author: future paper	
<b>STRUCTURE</b> 	See relevant sections: -human occupancy type -circulation: interior and ext. -security/life safety -building function -relation to work/recreation	-direct relation to configuration composition of atmospheric barriers -see individual configuration diagrams for affect of circulation, occupancy, etc. -dependent on form development	

## Expanding the concept of "Space Program".

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This paper is an overview of some efforts being developed in **Portugal** towards our future participation in space exploration and development. It lists strengths and problems Portugal has in this area, and suggests two ideas in space policy : The first idea is **"Flag of Cooperation"** and it hopes to improve the ability of international space law to solve the delicate problems posed by cooperation and competition in space. Portugal would register civilian spacecraft and structures owned by foreign citizens under it's national flag. Some consequences are examined. The second idea of **"Ocean Based Space Program"** tries to suggest a new policy to develop space commercialization today. Ocean settlement may be the missing first step that will allow space settlement to become cost-effective. Portugal may be an excellent " cradle " for the initial development of these new concepts because we already performed that function in history once before. In Portugal there is a deep predisposition for that kind of role in the world community.



## INFLATABLE HABITATION FOR THE LUNAR BASE

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In providing habitation for a lunar base, inflatable structures have a number of advantages over rigid modules, in packaging efficiency, convenience of expansion, flexibility, and psychological benefit to the inhabitants.

The relatively small rigid cylinders capable of fitting in the payload compartment of a launch vehicle are not as efficient volumetrically as a collapsible structure that, when packaged, fits into the same space but when deployed is much larger. Pressurized volume is a valuable resource. By providing that resource efficiently, in large units, labor-intensive external expansion (such as adding additional modules to the existing base) can be minimized. The expansive interior in an inflatable would facilitate rearrangement of the interior to suit the evolving needs of the base. This large, continuous volume also relieves claustrophobia, enhancing habitability and improving morale.

The purpose of this paper is to explore some of the aspects of inflatable habitat design, including structural and architectural considerations. Several different configurations will be considered: a sphere, a cylinder, and a torus.

## THERMAL TUNNELED FIRST STAGE LUNAR BASE

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A cost effective method for a first stage lunar base using indigenous materials could be achieved utilizing a thermal tunneling device. This system coupled with an infrastructure for future development and expansion of minning facilities, transportation routes and exploration camps shows promise in accelerating the pase of lunar development.

As has been seen in previuos studies of lunar habitats, they all involve heavy manufacturing of components and modules. These systems need to be launched from earth, sent to a lunar orbit and then deployed on the surface. It would seem applicable to use the existing lunar material to create the shell of these habitats; thus absorbing the cost of the heaviest component by using one that is indiginous to the lunar environment. As we have seen throughout history man has always used what is existing by being creative and resourceful we can eliminate a serious cost while at the same time creating a shielded habitat and a logical design.

The proposed scenario for this system would involve a) Constructing a thermal nuclear tunneling device, (all the components exist for this system but have not been put together for this purpose). There has been some testing of a similar device used for terrestrial matters. b) Using an expendable launching system the apparatus would be sent into lunar orbit, and soft landed on the surface. c) The system would then ignite and melt a tunnel into the lunar regolith, a pattern would be pre-programmed as per the requirements of the facility to be established. d) Some days later a landing crew would land and enter the tunnel; placing grapling hooks at the perimeter of the tunnel. A flexible membrane would then be hung from these hooks and then inflated to the required configuration. A microwave beam will be shot into the habitat thus hardening the inflated interior partitions. At this time entrance nodes would be placed at the surface and connecting to the tunneled habitat below. The habitat would then be pressurized and ready for habitation.

This general scenario gives ideas of alternative methods using existing materials and proceedures for a first stage lunar base. By exploring these other alternatives we can create a system that has a multiple uses, such as habitation areas with radiation protection, transportation routes and exploration camps without the expense of large components being launched from Earth.

## **THE HELIOX FACTORY CONCEPTS FOR LUNAR RESOURCE UTILIZATION**

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As Space Station becomes a reality in the next decade and planning goes forward for a return to the Moon and Mars as part of Pathfinder, detailed consideration will be given to utilization of lunar resources to provide propellants for space-based propulsion systems. Extraction and manufacturing processes are described for obtaining helium<sup>3</sup>, oxygen, and silane from lunar regolith. In addition, space-based propulsion systems are considered which could be fueled by these propellants.

An outline of the time scale during which routine cis-lunar operations take place is provided, as is a description of the kinds of missions embodied in these routine operations. Such missions include lunar surface to low lunar orbit, lunar orbit to GEO/LEO, and lunar orbit to Mars orbit. The requirements for oxygen and silane in chemical propulsion systems, and for helium<sup>3</sup> in fusion systems, are estimated using typical mass fractions, trip times, and frequencies.

Candidate extraction and manufacturing processes are developed and evaluated for the production of the required propellants, using various selection criteria. One key consideration is the amount of lunar regolith which must be processed to meet various propellant demands. Ancillary issues, such as storage, transport, maintenance, and testing, are addressed relative to the mission scenarios.

## EARTH-TO-SPACE ELECTROMAGNETIC LAUNCHER FOR LUNAR MISSION SUPPORT

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The cost of constructing and supplying a Lunar base would be greatly reduced if relatively low cost fuel were available in LEO. This fuel could be provided by an Electromagnetic Launcher (EML) which would deliver it to orbit in the form of water ice.(1,2) An orbiting facility would dissociate this water into usable propellant.(3) While the high accelerations inherent in an EML preclude its use for transporting living things or delicate equipment, additional savings could be realized by transporting construction materials and durable goods to orbit in the same way.

An analysis of the amount of fuel needed in LEO for the establishment and resupply of a Lunar base is made. Costs of transporting this fuel with an EML is compared with expected costs for conventional launch using chemical rockets and a scenario for construction of a Lunar base using EML is outlined. Significant cost savings as well as greatly improved transportation infrastructure for future missions can be attained through the use of electromagnetic launch technology.

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## THE SPACE STATION ENVIRONMENTAL HEALTH SUBSYSTEM

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Spacecraft utilized for extended duration spaceflights such as manned Mars missions as well as habitats used in extraterrestrial colonies such as lunar bases will probably include many operational features that will be first tried and tested onboard the Space Station. These features include continuous and permanent habitation, little or no opportunity for Earth based cleaning and maintenance of equipment, dependence on closed or partially closed environmental control systems, the recycling of potable and hygiene water, and the need for a large complement of potentially toxic utility chemicals. In addition, crew rescue in the event of illness or extensive contamination may not be possible. These constraints underscore the importance of comprehensive environmental health programs to help ensure and verify the continuous habitability of extended mission spacecraft and facilities.

This paper describes some of the general environmental health issues related to manned extraterrestrial environments, examines these issues as they apply to the Space Station, and focuses on the subsystem being developed to meet the environmental health needs of the Space Station, the Environmental Health Subsystem (EHS). Major EHS functions are explained and some of the EHS environmental monitoring instrumentation is described. A scenario describing EHS utilization during a Space Station chemical contamination event is also provided.



THE EVOLUTION OF PLANETARY EXPLORATION TECHNOLOGY FROM THE LUNAR  
OUTPOST. S. R. Sadin, Code RS, OAST, NASA/HDQ, Washington, DC 20546.

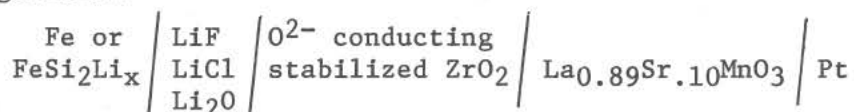
This paper examines the critical technology developments required for lunar outpost development and describes the individual strategies for their evolutionary transition for application to Mars and other planetary missions. The value of the inheritance of the lunar-derived technology capabilities for other planetary applications is assessed. The concept of a lunar laboratory for research and demonstration of planetary surface technologies is presented, suggesting an analog to use of the Space Station as a laboratory for on-orbit, in-space technology research and demonstration. The advantages of risk-reduction through the demonstration of first-time uses of planetary technology innovation at the lunar laboratory are discussed and the relative cost benefits of simulation at the lunar laboratory are compared with those at Earth. There is no attempt to prove the superiority of this evolutionary approach to planetary technology development but, rather, to examine another facet of the strategic exploration option of exploiting the Moon as a stepping stone to the planets.

ELECTROLYTIC CELL FOR LUNAR ORE REFINING  
AND ELECTRIC ENERGY STORAGE  
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A high temperature electrochemical cell has been identified capable of simultaneously generating oxygen and lithium from  $\text{Li}_2\text{O}$  dissolved in a molten salt. This cell utilizes an oxygen vacancy conducting solid electrolyte for effectively separating oxygen evolving and lithium reducing half-cell reactions. In practical cells to be developed, cathodically deposited liquid lithium would be continuously removed and used as a conveniently storable reducing agent for ore refining under lunar conditions, via the general chemical reaction:



where MO represents a lunar ore. The electrolytic cell possesses the general configuration



Major experimental observations found for this cell can be summarized as follows: 1) The ternary molten salt  $\text{Li}_2\text{O}$ -LiF-LiCl was identified as the preferred catholyte since it was capable of accommodating  $>30\text{m/o}$   $\text{Li}_2\text{O}$ , possessed both a low melting point  $<460^\circ\text{C}$  and high ionic conductivity. 2) Cathodic lithium deposition was Faradaic and possessed rapid electrode kinetics. 3) Thermodynamic measurements performed on  $\text{FeSi}_2\text{Li}_x$  electrodes showed the lithium deposition reaction to be endothermic but within a range readily compensatable by IR losses in practical cells. 4) Tubular electrolytic cells unequivocally demonstrated that only lithium and oxygen were respective cathode and anode reaction products from the ternary catholyte. 5) Cells in addition demonstrated high electrochemical reversibility and were shown to form the basis of the highest energy density secondary battery system identified to this time.

Under lunar conditions cathodically generated lithium would be continuously recycled between the lunar ore refining step, where it would become oxidized to  $\text{Li}_2\text{O}$ . After its sublimation from the solid-state reaction mixture it would be reintroduced into the electrolytic cell to again become electrochemically separated into liquid lithium and oxygen. In this way oxygen would be indirectly electrochemically extracted from lunar ores for breathing purposes, together with formation of the corresponding chemically reduced metal. It is important to note that lithium could be conveniently stored as a solid under lunar conditions and is a significantly stronger reducing agent than hydrogen. If photovoltaic electrical energy is the primary power source used, constant power into the electrolytic cell may be achieved by either introducing or removing electrical energy from a lithium/oxygen storage battery.

THE LUNAR SETTLEMENT TRADE BALANCE IN SERVICES: THE EARLY EXPORT OF OFFSHORE SERVICES AND THE DEVELOPMENT OF EARTH-BASED TELESERVICE INDUSTRIES TO SUPPORT SPACE-BASED DEVELOPMENT; J. Sanchez, P.O. Box 12625, Tucson, Arizona 85732

Portrayals of the early development of lunar settlements consistently focus on the development of manufacturing and/or mining enterprises as the central element in colony growth. However, the continuing problem of transportation costs will remain an obstacle for manufacturing growth for decades at least. The trade in services has been completely ignored but can become the basis for substantial exports blocked by no transportation penalty, can reduce the number of personnel needed to support any given industrial/mining activity, and will fuel the growth of a dynamic Earth-based industry delivering teleservices to space-based communities. Although there has been a certain consideration of the value of teleservices delivery (teleoperator systems, biotelemetry), a fuller range of such teleservices would include: telebanking, teleshopping, teleconferencing, telemedicine and remote learning systems. Admission of competitive teleservices provided by numerous vendors is the first step away from the lunar settlement as military-base or company-town to a freer and more innovative community. However, the major growth sector in the economy of the lunar settlement will be offshore services and corporate services. Following the model of other offshore centers, early products the lunar settlement could export include banking privacy, corporate shells, tax-free deposits, captive insurance facilities, secure data storage, and fiduciary services.

## LUNAR $^3\text{He}$ , FUSION PROPULSION, AND SPACE DEVELOPMENT, John F. Santarius, University of Wisconsin-Madison.

The recent identification of a substantial lunar resource of the fusion fuel  $^3\text{He}$  (1) may provide the first terrestrial market for a lunar commodity and, therefore, a major impetus to lunar development (2). The impact of this  $^3\text{He}$  resource—when burned in  $\text{D-}^3\text{He}$  magnetic confinement fusion reactors for power and propulsion—may be even more significant as an enabling technology for the exploration and development of space. This paper will address both  $\text{D-}^3\text{He}$  fusion propulsion and its impact on space development.

The reaction  $\text{D} + ^3\text{He} \rightarrow \text{p} (14.68 \text{ MeV}) + ^4\text{He} (3.67 \text{ MeV})$  produces about 95% of its power (including side reactions) in charged particles which may be converted to electricity at very high net efficiency (3) or may be channeled by a magnetic field to provide direct thrust. The high efficiencies of these processes lead to specific power values of 2-5 kW/kg (4). Since magnetic fields confine the  $\text{D-}^3\text{He}$  plasmas, temperatures are not limited by materials considerations, and typical burning plasma temperatures are 40-100 keV (500-1200 million K). Directly exhausting the plasma will lead to extremely high specific impulses (about  $10^6 \text{ s}$ ). Lower specific impulses are also available, ranging continuously from about  $10^5 \text{ s}$  to about 200 s, by adding matter to lower the exhaust plasma temperature but increase the thrust or by heating a gas with photon radiation in a blanket surrounding the plasma and then exhausting it. The thrust to weight ratios will range from about  $3 \times 10^{-4}$  to 0.03. Due to the high specific power values and to the flexibility inherent in the ability to tailor the thrust program to mission requirements, fusion propulsion will dominate future exploration and development of the solar system. Preliminary designs of fusion propulsion systems will be presented and their application to selected missions will be assessed. The implications of fusion power and propulsion as an enabling technology for long range missions and as a market for lunar  $^3\text{He}$  fuel will also be discussed.

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## BIOBEHAVIORAL CONSIDERATIONS FOR MANNING A LUNAR BASE

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The operation of a manned Lunar Base brings a special challenge to the biobehavioral sciences due to the combined physiological, emotional and social stresses which will affect its occupants. Mental health planning pre-mission, as well as physiological and psychological monitoring during the Lunar Base crew rotation will be necessary in order to prevent, diagnose and treat those biobehavioral disorders which could impact mission success or risk the health and safety of crewmembers. This paper will discuss these disorders and their diagnosis and management in a Lunar Base environment.



AN ANALYTICAL APPROACH TO SCHEDULING AND  
COORDINATING A LUNAR BASE INITIATIVE

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Successful implementation of a fully operational and economically viable lunar base will require, more than any previous or current NASA activity, the integration of many diverse infrastructure and technology development programs. A coordinated progression from a man-tended base to an autonomous facility will demand a time-phased approach to procuring, integrating and eventually managing the habitation, transportation, communication and utilization elements needed to support a sequential build-up in lunar base operations. The functional similarity between many of these elements, such as unmanned, heavy cargo landers and manned orbit/surface excursion vehicles, will warrant at least partial sharing of technology and hardware between different programs. In effect, the concept definition, preliminary design, full scale development and operational phases of different infrastructure programs and the demonstration milestones of key technology support programs will be linked to each other. For example, the preliminary design of a lunar base transportation node will be enabled by the successful demonstration of solid aluminum/LOX and regolith extraction/processing technology. By requiring an extensive and complex time-phased integration of many diverse activities, a lunar base initiative will be very sensitive to perturbations and delays in its supporting development programs. This paper describes the application of a scheduling and planning analysis tool, developed for the Office of Exploration at NASA Headquarters, for large-scale program management of a lunar base initiative. This tool has been used to identify the critical scheduling paths for a lunar base scenario and assess the programmatic effects caused by introducing perturbations in supporting program schedules and funding levels. This enables the analyses of scheduling impacts for different scenarios before substantial funds are committed to this initiative.

## Technology Development For Lunar Base Water Recycling

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A lunar base and other extended duration space missions will require the development of a life support system that minimizes resupply requirements. In order to accomplish this, NASA has initiated work on developing a controlled ecological life support system (CELSS) using mostly biological and other natural processes. One purpose of this system will be to recycle water for potable and other uses. The objective of this paper is to review the present art of water recycling and identify technology development activities required to support CELSS water reclamation development.

A review of current technology for recycling water indicates that terrestrial systems usually incorporate a combination of physical/chemical and biological processes. Such a combination of processes is probably a good choice for an initial lunar base water reclamation system particularly if the biological systems support oxygen regeneration and food production. Unfortunately, biological processes are presently considered too unreliable for space program applications. Thus, considerable research and development work will be required before a controlled ecological system based substantially on biological processes is developed.

With respect to water recycling technology, development activities will be required in the areas of water and waste processing systems and water quality monitoring instrumentation. Since little work has been done with processing wastes under lunar or space conditions, a major effort to develop these types of systems is needed. Processes that need to be evaluated include biological oxidation, wet oxidation, nutrient removal and recovery, and solids dewatering. Additional work will also be required to integrate current potable water treatment processes such as filtration, adsorption, and disinfection into the CELSS. Instrumentation for measuring contaminants in water is necessary in order to control the water reclamation processes and monitor water quality acceptability. Monitors that measure nutrients, specific organics, and trace inorganics will need particular attention.

Another area of concern is the development of water quality standards for various uses. These standards are needed to guide the development of the water reclamation systems and ensure that the health of the crew is maintained. Since terrestrial standards do not consider direct recycle of water, they are not entirely applicable to CELSS. These standards must account for possible problems caused by the use of closed systems on a small scale. These problems include the release of volatile organics by plants, the bioaccumulation of toxics and trace minerals, the increased potential for disease transmission by waterborne routes, and the formation of disinfectant byproducts.

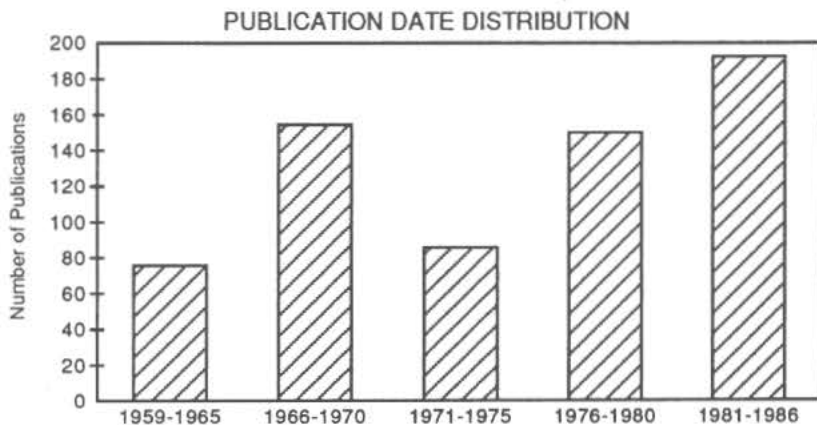
## A LUNAR BASE BIBLIOGRAPHY

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The effort to orchestrate a Lunar Base will involve volumes of information scattered across many fields and stretching back at least twenty years. In order to support this multi-disciplined effort, a data base covering information on the various aspects of Lunar Base would be a useful asset. It should include not only published literature but also information in various forms, such as blueprints, building and hardware specifications, and government 'gray' literature. It would allow those in one field to quickly determine what information is available in another field without having to be familiar with that field's references and resources.

Towards this end, the Planetary Materials Branch at JSC, NASA has begun to compile a bibliography. At present there are over 600 entries in the bibliography and this number should double by the time of the Conference. We have gleaned what we could from resident offices, searched thirty-seven databases and incorporated references supplied by Paul D. Lowman, Jr. in an April 1984 bibliography.<sup>1</sup> The Lunar Base Bibliography covers a diverse range of subjects such as hydrology, international law, mechanical engineering, human physiology, planetary science and many more. The following chart gives the total number of publications we presently have for five different ranges of dates.



The bibliography is stored on the Branch computer account and is searchable by author and/or keyword. This allows the bibliography to be as broad as possible while still allowing the user to quickly find the specific references needed.

In order to make this a useful tool, we welcome additions to this bibliography from the community which will use it. We are looking for future work and research as well as past research and reports that we have missed. We can be contacted at the following address:

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(713)483-5007  
(FTS)525-5007

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## LUNAR ARCHITECTURE AND URBANISM

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Material expression of manned space activities in the past was governed completely by engineered solutions to the harsh constraints of a new flight environment, using available methods and familiar hardware. Even current attempts to design missions (planned for groups working over months) depend still on the old methods, augmented by a new specialty: human "factors". That very name, as well as the reductionist menu of subjects it subsumes, shows clearly how embarrassingly novel it is for a space program specialized in engineering to grapple with the messy problem of architecture.

We may define architecture as the professional activity of coordinating a set of specialty industries and services for the purpose of making facilities to enhance human life. Taken in its most general sense, the "second-oldest profession" includes everything from spoons to highways, gardens to sewers, and buildings too. Civilization and architecture have defined each other for over 5000 years on Earth. Evidently, problems in human use which remain (despite five millennia of practice) will not be solved in any deep way, especially in space's extreme setting, merely by the new "human factors" emphasis. Future attempts at architecture in space, and particularly on the Moon, must adopt a broader approach.

Recasting the conventional question --- what Architecture can offer the Space Program --- into the more useful form of what space will do to architecture, allows us to recognize that within a few decades, the way we use space hardware will largely eclipse the facts of that hardware in our social awareness. That is, merely knowing what kinds of infrastructure we might provide on the Moon does not at all solve the problem of projecting civilization into that infrastructure. Orbiting a few people has been one thing; sustaining many will be quite a bit more interesting. But enabling several dozen to grow into the several hundred or several thousand of a lunar society will be a completely different problem, requiring extensive preparation that our vague notions of "colonization" do not begin to provide. We are much closer to wanting, and being able to put, societies on the Moon than we are to ensuring their viability once there.

What role will space play in future architecture? Currently a spacecraft systems engineer acts as proto-architect by coordinating the detailed design of subsystems like thermal control, propulsion and structure so they add up to a functioning vehicle. Analogously, the lunar architect will coordinate the work of specialists in spacecraft engineering, planetary geology, structures, construction, CELSS, human factors, environmental preservation, and many others, to produce a tenable extraterrestrial urbanism. Ironically, it is a shorter leap from present architecture to space architecture than it is from present space engineering to the same end, because the problems of human use and enrichment, which will inevitably overshadow technical challenges (in space as on Earth), cannot be solved best by finite element codes on Crays. The fine multi-variate balance required must still arise from human wisdom.

The lunar architect must therefore know something of all the disciplines which contribute to urban design, including not only the standard complement of space specialties, but also the history of human solutions to building, human responses to proportions, character, symbolism and scale, and urban planning. Serious education for this renaissance array cannot be premature.



## ENGINEERING PLANETARY LASERS FOR INTERSTELLAR COMMUNICATION

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A major driver for expanding lunar civilization will be the projects that it alone can enable. Large, complex, distributed missions for the inner solar system will both require and define extensive lunar industry and expertise. The most elaborate use of such resources yet proposed is construction of a planetary laser for wideband deep-space communication, the feasibility of which is established by this work.

Natural solar-pumped CO<sub>2</sub> laser amplification has been observed and modeled in the mesospheres of Mars and Venus [1]. Harnessing laser energy from such vast gain media could allow efficient communication over great distances. Astrodynamical, environmental and gravitational constancy favor Venus. Multi-satellite relay stations in a high circular equatorial orbit can extract laser energy along tangential lines of sight through the atmosphere. A pentagonal split-ring resonator optimizes system performance. The satellites are large (order km) actively intelligent structures consisting of hierarchically distributed sensors, processors and actuators. Each is surfaced ultimately by an array of cooperative mirrors designed for optimum infrared performance. The fleet controller learns to compensate in detail the periodic perturbations of its environment, updating the actual system state several times each second.

Ion engines perform station-keeping. Large diameter dual annular momentum rings allow fast, vibration-free 3-axis attitude control. Electrical power for propulsion, stabilization, datonics and mirror control, and momentum balance counter-mass are all provided for each satellite by nuclear reactors. A Littrow diffraction grating blazed to select the P(12) CO<sub>2</sub> line for oscillation couples out 3 % of the circulating cavity power. This 180 kW beam, once redirected to modulators at Venus' L1 and L2 points, allows virtually constant duty cycle to most any point on the celestial sphere.

Achievable low-error data transfer rates are limited by a priori knowledge of target size more than by either pointing accuracy or stellar proper motion uncertainty. Presuming heterodyne detection with a 100 m receiver, this laser, if used as a SETI signal aimed at a stellar "habitable zone" the size of Jupiter's orbit, can transmit tens of kbps to 25 pc, a volume of space containing over 700 approximately solar-type stars. For CETI (once contact had been made), or for sending information to human-launched [2] stellar probes, where a 1 km receiver can be presumed within a 1 AU orbit, data rates of hundreds of Gbps can be achieved to 10 light years.

The prospect of near-term technology transmitting exa-bits per year to other star systems has direct eventual consequences for enabling practical interstellar transportation for humanity, particularly if nanotechnological recording and assembly [3] become possible. Engineering planetary lasers thus represents a most exciting 21st century space activity requiring a mature space industry, to which the Moon is the key.

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ILMENITES IN OCEANUS PROCELLARUM. V.V. Shevchenko, V.V. Busarev, Sternberg State Astronomical Institute, Moscow University, Moscow 119899, USSR

The presence of ilmenite as an oxygen-containing mineral is an essential parameter in choosing prospective regions on the Moon for study and exploitation<sup>2</sup>. As an ore mineral, its highest concentration (up to 20%) is observed for mare basalts with the largest content of titanium. Ilmenite basalts are only encountered on the lunar surface in regions whose genesis has not been thoroughly studied. A forecast for ilmenite-basalt regions can be made with the help of methods of planetary astronomy. In general, ilmenite basalts are probably present in the central and western parts of Oceanus Procellarum, in addition to the Apollos 11 and 17 landing sites where they have been sampled. Ground-based photographs and those taken aboard interplanetary station Zond-6 have revealed in the northwestern part of Oceanus Procellarum some comparatively small regions which have the lowest albedo on the lunar surface, <6%. Figure 1 shows the regions which, by albedo and spectrozonal parameters (3), apparently are sites of elevated  $\text{TiO}_2$  content in surface rocks.

Additional data are spectra for a region northwest of crater Lichtenberg, which have been obtained for the 0.336-0.758  $\mu\text{m}$  range with a resolution of 0.0048  $\mu\text{m}$ . The observations were made in May, 1987, in the Crimea on the Zeiss-600 telescope. Figure 2 compares spectra inside the region (plots 1, 2) and the spectrum of the Apollo 17 landing site (plot 3), which was obtained at that time. Comparison of the spectra indicates that the characteristic absorption band in the 0.5-0.6  $\mu\text{m}$  range manifests itself quite distinctly. Some features of the spectra coincide quite well which may be attributed to an elevated content of ilmenites in the surface rocks of the region northwest of crater Lichtenberg.

Empirical dependence of the spectrum's slope on the percentage  $\text{TiO}_2$  content<sup>1</sup> gives values of 5.3% and 6.8% for plots 1 and 2, respectively. Since all the other plots shown in Fig. 1 have similar optical properties, the estimates obtained can be assigned to them too.

Of special interest is the inner region of the crater Grimaldi. Figure 3 gives the isotonal image of the crater that was obtained from a Zond-8 photograph. Grimaldi is 170km in diameter and its floor was flooded by lava flows with a very low albedo. Arrows inside the crater indicate two areas with albedo less than 6%. Surface rocks at the floor of the crater, especially in its southern, the darkest region, are very likely ilmenite basalts.

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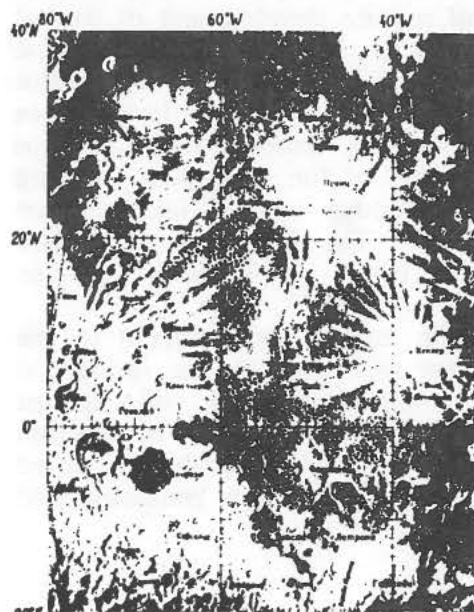


Fig. 1.

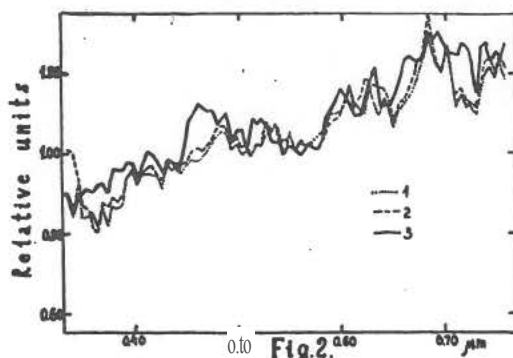


Fig. 2.



Fig. 3.

Fig. 1. Areas in the western part of Oceanus Procellarum with supposed higher content of titanium oxide in the surface rocks according to optical data. The reflectance spectra 1 and 2 in Fig. 2 correspond to plots L-1 and L-2 near crater Lichtenberg.

Fig. 2. The reflectance spectra of lunar surface: 1 - plot 1 ( $\lambda = 72.9^\circ\text{W}$ ,  $\beta = 35.0^\circ\text{N}$ ) and 2 - plot 2 ( $\lambda = 75.1^\circ\text{W}$ ,  $\beta = 32.7^\circ\text{N}$ ) near crater Lichtenberg, 3 - plot at the landing site of Apollo 17.

Fig. 3. Isotonal image of crater Grimaldi according to the photograph obtained by "Zond-8". The areas indicated by arrows have albedo less than 6%.

HOT PRESSING OF LUNAR SOIL AND QUALIFICATION FOR MANNED APPLICATIONS;  
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Simple solar heated equipment can bond Lunar material into useful construction materials using. The process involves modeling soil into simple shapes such as bricks, cylinders, or segments of spheres or cylinders. Then the material is heated to about 1000°C in the presence of a stress of a few tens of bars. The process seems appropriate for building a permanently manned base with minimum mass delivered from earth.

Thermal bonding of lunar soil occurred naturally to form soil breccia blocks up to several meters across observed by Apollo. Glass sintering is also in part responsible for forming glass bonded grains, agglutinates. Studies of returned lunar material and vitreous simulants by Simonds and Klein, demonstrate the viability of the process. Although all lunar soil contains glass and thus can be utilized the better glass forming compositions characteristic of non-mare sites are more tractable. The reason that non-mare soils are more readily sintered is that their glass component crystallizes more slowly at temperatures at which glasses flow than mare soil glasses. Sintering without application of external stress can remove much of the porosity. However, fabrication of low permeability materials will require application of external stress of a few tens of bars.

The formation of hot pressed ceramics is suggested to be of for load bearing construction (masonry), fluid conduits and tanks. The hot pressed materials can be made gas tight by application of coatings, such as plastic film or metal foils. The ceramic pressure vessels potentially could be used for crew activity in a shirt sleeve environment. Such an application of these materials will require development of formal NASA spacecraft verification procedures suitable for the new materials. The critical verification needs include: a) pressure vessel certification, b) demonstration of control of fracture propagation and c) demonstration that the pressure vessel will leak before it will rupture. Pressure vessel testing involves pumping the vessel without loss of pressure to a predetermined multiple (typically 1.4- 2 times) of the maximum working pressure. Fracture control will have to be accomplished through use of flexible films and coatings, since the ceramics themselves are brittle. The leak before rupture requirement can also be met by flexible and stretchable film. Such films can also reduce the leak rate of the pressure vessels.

For hot pressing to be practical it must reduce the total mass delivered to the moon. The trade is determining the reduction in mass delivered to the moon for structural support, pressure vessels, conduit and tanks made from lunar soil, against the mass of a) the solar collector, b) materials handling equipment c) compaction equipment and molds d) instrumentation, e) additional life support consumables required for the crew while manufacturing the materials and f) any coatings or films and associated application equipment.

**RESOURCE EXPLORATION AND DEVELOPMENT AT A PERMANENTLY STAFFED LUNAR BASE:** Charles H. Simonds, Eagle Engineering, Inc., 711 Bay Area Blvd., Suite 315, Webster, TX 77598

The history of the extractive industries is littered with stories of the economic failure of mines located on ore bodies that proved too small or had ore that could not be processed. Likewise offshore oil and gas platforms costing tens to hundreds of millions of dollars have been located on fields too small to justify the investment. A lunar mineral industry should not make similar mistakes. Developing a lunar resource plant, gravel pit, mine or oil field involves a similar series of steps: 1) locating the resource, 2) determining how much there is 3) determining the optimal method of extraction, 4) designing the excavation, and 5) the day to day planning of where to dig or drill.

1) The exploration program will begin with a polar orbiting satellite, which will not be discussed further.

2) Determining the volume of the resource requires space qualified variations of drilling, geophysical logging, geochemical sniffing, reflection seismic, electrical sounding. Holes will probably have to be drilled on a regular spacing which is a function of the resource. Analysis will probably be done by down hole measurements (logging) supplemented by analysis of cores of selected holes. The measurements are plotted on a map, the volume of reserve calculated.

3) Simultaneously with the reserve estimating activities final earth based or lunar based pilot plant studies will be needed to determine the optimal<sup>3</sup> beneficiation techniques. These studies will require a large volume, at least a few m<sup>3</sup> of the potential lunar ore. Both beneficiation and marketability must be considered and its schedule and cost impact analyzed. Definition of performance requirements for lunar resource utilization scenarios for characterizing volatiles in soil requires definition of how the volatiles will be extracted. If the volatiles are trapped as ice in soil, they probably would be extracted by excavating the soil, placing it in a pressurized retort and then heating it and driving off the gases and then condensing them. If on the other hand the volatiles are trapped at depth, it might be necessary to extract them in situ by heating and collecting the vapor. If the volatiles are chemically bound, then the mineral concentration will have to be found, and a method developed for separating the hydrous phases and then removing them, again in some sort of pressurized retort.

4) Designing a lunar mine or well field requires that the geometry of the resource body its concentration and lateral continuity be known at a level of detail greater than needed for simple volumetric estimates. Key factors include ability of the processing system to respond to variations in the feed stock, the anticipated variation in the natural material, the ability of the excavation or extraction system to select only the material compatible with the processing system and the geometry of the proper material. For example, if a process requires glass rich lunar soil for ceramics, it may be necessary to skim off only the top few cm or tens of centimeters, where the glass content is highest. In order to plan such an excavation program, the lateral and vertical continuity of the mature glass rich soil must be determined. For that application cores could be analyzed with a magnetic susceptibility tool or a down hole version of that tool. All Volatiles, whether in pres or chemically bound are readily measured by down hole instrumentation with gas detectors. Analysis of other resources is better done one cores or cuttings in a simple laboratory analogous to a mud logging trailer in the petroleum industry. This laboratory would typically have binocular microscopes, some thin section capability, moderate precision chemical analytical equipment and possibly a bench scale mineral separation facility to yield results correlatable to the full scale or pilot plant being serviced.

5) Guidance of the day to day operation of a mine or involves analysis of both the progress of the excavation and the operation of the extraction plant. Subtle variations with feed stock may greatly affect the operation of the plant.

## CONCEPTUAL DESIGN OF A LUNAR BASE THERMAL CONTROL SYSTEM;

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Space Station and advanced development thermal control technologies were evaluated for Lunar Base applications. The Space Station technologies consisted of single phase pumped water loops for sensible and latent heat removal from the cabin internal environment and two-phase ammonia loops for the transportation and rejection of these heat loads to the external environment. Alternate advanced technologies were identified for those areas where Space Station technologies proved to be incompatible with the lunar environment. Areas were also identified where lunar resources could enhance the thermal control system. The internal acquisition subsystem essentially remained the same, while modifications were needed for the transportation and rejection subsystems due to the extreme temperature variations on the lunar surface. The alternate technologies examined to accommodate the high daytime temperatures incorporated: lunar surface insulating blankets, refrigeration systems, shading, and lunar soil. Other technologies, such as louvers, were examined to prevent radiator freeze up during the low lunar night time temperatures. The impact of the geographic location of the lunar base and the orientation of the radiators were also examined. Trade studies were performed to generate an optimum baseline design which minimizes weight, power, and volume.



AUTOMATION AND ROBOTICS CONSIDERATIONS FOR A LUNAR BASE  
Nancy E. Sliwa, NASA Langley Research Center

The establishment of a permanent, crewed lunar outpost will require the development and use of advanced automation techniques, in both telerobotics (remote computer-assisted manipulation of equipment) and systems autonomy (intelligent automated control, monitoring, and diagnosis). These techniques are required due to the exposure limitations of humans working on the lunar surface, to the high-reliability requirements of systems in the harsh and remote lunar environment, and to the necessity of performing round-the-clock activities such as materials processing and scientific experiment monitoring.

A number of tasks that are expected to require automation in a lunar base environment were considered. These tasks include: the mining, processing, storage and transfer activities associated with LOX production; habitation module handling, transportation, and interconnection; soil movement activities for site preparation and hab module protection; structural assembly; solar and radiator panel installation and replacement; exploration and core sample retrieval; and remote experiment tending and inspection. These tasks deal primarily with external surface activities; self-contained internal automation, such as that dealing with enclosed plant and animal tending, crew module maintenance, or specific materials processing, were not examined in detail.

General criteria for lunar automated systems have been determined to be (1) hardware and software component modularity, (2) maximum hardware and software module replication, (3) multi- and mixed-mode operability, (4) autonomous fault trend analysis, fault detection, and fault-scaled operation/reconfiguration, and (5) improved validatability. Specific technologies that will be critical to successful automation include multi-manipulator control integrated with mobility, improved sensor control capabilities, lunar-tolerant mechanisms and processors, knowledge-based systems for process and fault management, and multi-purpose software architectures that integrate symbolic and numeric control capabilities. These criteria and technologies will be discussed in this paper.

Much of the necessary technology is expected to be available to NASA as a result of Space Station automation and robotics development and operations. However, all areas will require some degree of growth to accommodate the lunar surface, and certain specific problems will require unique solutions. This paper addresses these problems in more detail.

This assessment of lunar base automation and robotics has been performed by the Automation Technology Branch of NASA Langley Research Center, based on the branch's continuing research activity in space-based automation and robotics. Scenarios and constraint data were contributed by the Langley Spacecraft Analysis Branch, based on their investigations of thermal, environmental, and transportation requirements for a lunar base.



THE MISSIONS AND SUPPORTING ELEMENTS DATA BASE:  
ITS PURPOSE, STRUCTURE, AND USE; M. D. Sluka, Lockheed  
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The Missions and Supporting Elements Data Base (MSDB) is discussed. Its history, structure, and use is presented.

Under contract to the JSC Office of Exploration, the MSDB was configured to hold mission proposals and supporting element descriptions for Lunar base activities and Mars missions. It is similar to the Civil Needs Data Base (CNDB), but holds additional information not found in the CNDB. This extra data consists of, for example, precursor missions, manpower requirements, and resupply missions.

The MSDB is a pc based data base constructed using R:BASE system V software. Initially, it will be used for, among other things, input to the Lunar Base Integration Model developed by the Large Scale Programs Institute for NASA. As such, it incorporates all data required by the model. In the future, selected missions and support elements will be submitted for approval, and approved entries will be incorporated into the CNDB as planned activities for US space efforts.

Data input forms are presented for adding missions or support element descriptions to the data base. The aerospace community is invited to submit mission proposals and help out with data for incomplete entries.

FANTASY TO REALITY: THE BRIDGE TO PROGRESS

Michele Small  
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The dissemination of information can be exciting and fun. The learning aids that work best are the ones that put the information into a format that can be integrated into the fantasy life of the student. Films work wonderfully because people are visual thinkers; we call up an event or series of visual cues that help us remember. When science and mathematics are put into fantastic settings, the lessons presented can often be taught better than through lectures.

Imagination allows us to visualize what we want and how to get it. If that ability is discouraged, our society will become stagnant. Children are our greatest resource and their minds must be encouraged to dream of things both possible and impossible in order to help them develop both the confidence and the sense of play that is so often linked with invention.

The sense of fun that comes naturally to young people can easily be discouraged by the educational system we entrust with the task of teaching science. The justification is often, "Learning is serious business." Children are not miniature adults, and they can be easily bored. Dull, pedantic, information just won't fly. Educational films must keep pace with the pulse of childhood. It is well worth the extra effort to create first rate entertainment that imparts knowledge.

Clips from some of the films that have been most successful in promoting interest in the sciences will be included in my talk. They are:

The Unchained Goddess, produced by Frank Capra for Bell Labs, 1956. Subject: The weather.

Donald Duck in Mathematicsland, Disney Studios, 1956.

Men in Space, Disney Studios, 1956. From a series of programs on space exploration.

A film on the theory of relativity by Max Fleischer Studios, circa 1920-1930. The Fleischer Studios produced the Betty Boop cartoons.

Uniform Circular Motion in Physics, episode nine of The Mechanical Universe series produced by California Institute of Technology, 1985-86. Computer graphics animation.

2010, "Aerobraking sequence", MGM, 1983.

# WHY THE MOON IS THE BEST PLACE IN THE SOLAR SYSTEM FROM WHICH TO DO ASTRONOMY; H. J. Smith, McDonald Observatory, University of Texas at Austin

Groundbased astronomy, because of its overwhelming convenience and economy, will be with us for the long foreseeable future in spite of the blanket of atmosphere which limits the wide-field resolution of very large telescopes to little better than a second of arc -- a hundredth of their theoretical power -- and which restricts their spectral coverage to portions of a couple of decades.

Near-earth orbit with its relatively easy access to space offers enough improvement to have warranted the enormous astronomical efforts of the past three decades, with more to come. But severe difficulties will always be present. The most important of these, in no particular order, are: a) high orbital velocity with attendant (and rapidly growing) threat of damaging or totally destructive encounters with debris, b) the impact of and glow from energetic gas atoms, c) trash of all kinds from simple molecules on up which tends to follow and surround any free-flying system, d) the brevity of exposures, e) the very high cost of accurate aiming and guiding of free fliers, f) the difficulty of precise station-keeping for long-baseline systems, g) the problem of access to free fliers for maintenance and instrument changes, and h) the large and expensive ground-support systems needed to operate them.

The moon, once permanent bases have been established, wins on nearly every count. Key points, again in no special order, include: a) the lunar vacuum is superb, b) the quiet, stable lunar surface allows installation of simple telescopes and other instruments similar to but even cheaper than their low-cost terrestrial counterparts thanks to the weak lunar gravity, c) this gravity keeps the environment scrupulously clean, d) the slow lunar rotation allows continuous exposures of up to weeks duration if desired, yet brings all the sky into view, e) with simple sun- and ground-shields, even the daytime sky will be good for a great deal of astronomy, f) natural cooling to very low temperature for infrared work likewise follows simply by keeping the telescope shielded from sun and ground, g) the moon is a prodigious source of raw materials for base structures and shielding, h) enormous, virtually perfectly stable interferometric structures ranging up to several thousand kilometer baselines will be straightforward to operate, i) natural craters of virtually perfect shape will, in the low lunar gravity, allow eventual construction of filled-aperture "Arecibo" up to kilometers in diameter, j) installation and maintenance (to be sure with robotic assistance) will be straightforward and cheap -- "walk out with a screwdriver and fix it", k) small, earth-like staffs will suffice for operation, and l) the lunar back-side is the only place from which the electromagnetically polluting earth can never be seen.

## Gas-Sealing Abilities of Bedrock in an Underground Lunar Base

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The natural rock walls of an excavated underground lunar habitat could be utilized as the primary atmospheric seal, provided all natural fractures in the rock are plugged, and the rock matrix itself is sufficiently impermeable to gas. Permeability and porosity measurements made on four types of igneous rock revealed some interesting correlations between rock type and gas permeability. Analyses on basalt, diabase, norite gabbro and granite revealed that porosity in the mafic rocks was highest in the basalt (4.7%), lower in the diabase (0.65%) and less than 0.5% for the norite. Permeability of these rocks to gas, Klinkenberg-corrected, ranged from 2.64 microdarcies in the basalt, down to 12 nanodarcies in the diabase, and was below the measurement resolution of the equipment (0.2 nanodarcy) for the norite. The granite had a measured porosity of 0.59%, similar to the diabase, and a gas permeability of 0.9 microdarcy. The data reported here were all obtained with a net confining stress of 2000 psi (13.8 MPa) imposed on the rocks. Lower net stress would result in higher values, especially for the permeability. Petrographic observations were also made to compare rock pore geometry with measured gas flow parameters.

In the mafic rocks, there is a distinct trend of decreasing porosity and permeability with increasing depth of emplacement. Petrography reveals that the extrusive basalt, a common lunar mare rock type, owes its high porosity to vesicles formed by gas bubbles in the lava. Microfractures connecting these voids are responsible for the high permeability. The diabase, a shallow intrusive, contains far fewer and smaller vesicles and poorly interconnected microfractures, accounting for its lower porosity and permeability. The deep, plutonic norite, a common rock type in the lunar highlands, contains no vesicles and very short, discontinuous grain boundary microfractures, resulting in very low porosity and permeability.

If it is found that the much lower lithostatic and tectonic stress gradients on the moon do not lead to greatly increased rock permeabilities at excavation depths, a lunar norite may provide a sufficient gas seal for the atmosphere of an underground lunar base. This would save significantly on construction costs involved in placing airtight barriers on every internal wall, and also provide aesthetically pleasing rooms with walls composed of natural rock, instead of an artificial sealant material. The small amount of data collected thus far indicates that construction plans for a lunar habitat excavated into a uniform pluton of norite could, after sealing any natural fractures, safely leave the natural rock walls uncovered as an adequate atmospheric pressure barrier.

## SOLAR WATER HEATING SYSTEM FOR A LUNAR BASE

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A lunar base will require 120°-180°F hot water for washing, food preparation, clothes and dish drying, environmental heating, and processing waste water. A solar collector system is proposed to directly heat the water. This system should be cheaper, more efficient and require less maintenance than an equivalent solar dynamic or photovoltaic electric system.

To determine the feasibility of the system, computer models of the input energy, system functions, and hot water usage have been developed. These models have been used to determine the system performance (energy collected and stored) as a function of lunar latitude, collector type (flat-plate or concentrator), tilt and orientation (flat plate), operation (heat pipe or pumped, single-phase fluid), collector size, absorptivity, emissivity, storage volume, and load based on the number of people.

Because of the long lunar day and night, a large storage mass is needed compared to the collector size. Other results indicate that a high  $\alpha/\epsilon$  is necessary to maintain a reasonable collector size and that flat-plate collectors perform well in a wide band of tilts and orientations. Ratios of the system collector area and storage mass versus the manning level are presented, and the predicted system performance is shown in a series of graphs.



### The Asteroid Infrastructure

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Criswell's "Demandite" [1] concept is generalized in this admittedly speculative paper to include energy and information in addition to materials, and applied to deduce aspects of the transportation, energy and information infrastructure of future human activity around the known asteroids. Although minimum  $\Delta V$ 's required for propulsion within the asteroid belt are relatively low compared to near-earth space, the distances to be covered are in general great with longish waits (200 years is not uncommon) between favorable launch opportunities. (Might one thus expect asteroid dwellers to be "pack rats" relative to earthlings?) Trajectory parameters between a hypothetical set of trading locations, including earth, Mars and Jupiter, are presented to illustrate transportation constraints.

However, information and energy may turn out to be more precious commodities to asteroid dwellers than mere materials. Although they are well suited for observation within and outside the solar system, the asteroids are a poor place to collect, analyze or archive data. Thus we may expect a relatively radial flow of information between the asteroids and near-earth space.

An analysis of the relative importance of chemical and solar energy sources to the asteroid infrastructure is also performed.

Perhaps the most significant conclusion from the work described is that low value products tend to be traded circumferentially along orbits while higher value products can be expected to go more direct radial routes.

[1] Ref: Criswell, D. R., "Demandite, Lunar Materials and Space Industrialization", in Grey, J., (Ed.), Space Manufacturing Facilities II, AIAA, New York, 1977.

THE ROLES OF HUMANS AND ROBOTS AS FIELD GEOLOGISTS ON THE MOON;  
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Lunar geoscience investigations will figure prominently at a lunar base. It is not too soon to consider the relative merits of several methods of performing geologic field work to prepare for base establishment and to conduct exploration from the base. We distinguish here two types of field work: geologic reconnaissance, the quick and superficial examination of a given site or region with the aim of understanding broad geologic features; and geologic field study, in which extensive and protracted work is performed to formulate and answer specific scientific questions about geologic processes and history. Both types of geologic exploration are needed, but they require different hardware and approaches.

Two steps should precede establishment of a lunar base. (1) A lunar polar-orbiting mission should be flown to complete our global database of surface chemistry and mineralogy. (2) Samples should be obtained from a variety of lunar surface units. This phase of geologic reconnaissance can best be performed by an inexpensive series of simple sample returners of the Soviet Luna type. Because many lunar units are geologically complex and difficult to interpret, this phase of sampling should involve only certain types of targets where interpretation of the returned samples is relatively straightforward; such targets would include compositionally distinct mare basalts, impact melt sheets of certain large complex craters such as Copernicus (to calibrate the lunar absolute time scale and provide information on terra compositions), terra regions that appear petrologically interesting in the orbital data, and materials of potential utilization interest (e.g., volatiles on pyroclastics). Such a sampling program would provide data not only to address basic lunar science questions but also to help select a site for the lunar base.

To completely understand lunar evolution and history, geologists must conduct intensive field studies of promising areas on the Moon. Examples of such targets include the central peaks of large craters where complex outcrops occur, megablocks of brecciated highland crust that occur both as ejecta and as exposures within crater walls, in situ mare basalt exposures such as occur within the walls of sinuous rilles, crater and basin ejecta deposits, and specific lunar landforms such as volcanic vents and wrinkle ridges. A Luna-type sample return from such targets would probably produce more confusion than enlightenment. Direct human involvement and control is required at this level of study.

Given such a requirement, what techniques are best suited to accomplish these scientific goals? For such complex surface operations, we envision two basic approaches: human field geologists and teleoperated robots. The use of teleoperated robots heretofore has not received detailed consideration, but they have many potential advantages over human field geologists. Robots would have sensory capacities at any wavelength in the electromagnetic spectrum, great physical strength and endurance, and the ability to work in the harsh lunar environment unencumbered by complex life-support systems. Such machines would be under the direct control of scientists who would remain at the lunar base. The robots would make extensive or intensive traverses of selected regions and return samples to the base for extended analysis. In contrast, human field exploration would need extensive machine support and would have to be carefully planned and of short duration to minimize risks from radiation exposure and possibly injury. However, human field workers would have advantages over remotely controlled robots in mobility and small-scale dexterity, and in the intangible (but important) sense of personal involvement.

We suggest that a combination of these two techniques for geologic exploration from a lunar base is highly desirable. We envision initial field operations in the vicinity of the base involving both humans and robots; such work would calibrate the robot explorers and give valuable experience and confidence to their controllers in future operations. This phase would be followed by a series of extended traverses and by intensive field work at complex field sites, both to be done by the robot field workers under human control. Such a series of traverses would constitute the bulk of lunar exploration, with periodic returns of the robots to the base to return samples and receive maintenance. The results of these explorations would be used to plan short followup visits by human geologists to sites of exceptional scientific interest or to sites whose complexity exceeds the capability of teleoperations. This method of operation would make a single-site base into a "global" lunar base through the use of a central operations center for long robot traverses without the cost or weight encumbrances of human life-support facilities. This strategy of base operations would work equally well at bases on Mars and other terrestrial planetary bodies.

**THE FLIGHT DYNAMICS OF A TRANSPORTATION NODE;**

J. M. Stecklein, ED23, NASA Johnson Space Center

A transportation node (TN) supporting the Lunar Base Program must store large quantities of propellant and handle frequent vehicle interactions. These interactions include docking of vehicles, transfer of propellant, mating of payloads and vehicle elements, and deployment of lunar transfer vehicles. This paper discusses the impact of propellant dynamics, vehicle docking, and other related disturbances on the attitude, control, and stability of a low Earth orbit TN.

Space Systems Integrated Simulation (SPASIS), a six degree-of-freedom on-orbit spacecraft simulation developed by the Advanced Programs Office at NASA JSC, will be used to calculate the forces and torques on the TN due to propellant motion, vehicle docking, control system reactions, and the on-orbit environment. Two TN configurations will be studied: the Platform Servicing Station and a version of the Dual Keel Space Station. The Platform Servicing Station was designed to be heavily gravity gradient stable and optimized for TN functions. This configuration is compared with the Dual Keel design, a growth version of the current Space Station design. The two configurations are compared in three activity scenarios: steady state conditions, spacecraft arrival and docking at the TN, and lunar transfer vehicle departure. Based on these results, guidelines are established for creating conceptual designs of a transportation node.

LUNAR OBSERVATORY OCEAN/ATMOSPHERE MONITORING  
AND ANALYSIS FOR GLOBAL CHANGE

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Long term global atmospheric/oceanic (and land) changes and interactions may best be detectable, monitored and analyzed from an earth-facing manned/unmanned lunar observatory.

Powerful optical, IR/microwave sensors continuously viewing the earth from the moon's stable base, could uniquely show global atmospheric, oceanic, polar and other phenomena. Atmosphere/ocean composition, temperature and other parameters affecting climate impact, etc., would be detectable with high resolution.

During a sun/earth ("lunar") eclipse the vignetted earth's atmospheric turbulence, "boil off," meteor dust concentrations, etc., would yield valuable aerological data. Also, solar "wind" would be detected, as well as its influence on atmospheric ionization, and ocean/atmosphere exchanges.

The author will describe a "suitable" lunar observatory, also useful for astronomical purposes, and discuss concomitant advanced technology, data management, etc.

ADVANCED PROPULSION FOR LEO-MOON TRANSPORT: I. OVERVIEW; M. O. Stern, California Space Institute, University of California at San Diego, La Jolla, CA 92037.

The next four abstracts report on a study supported under a NASA grant through Barney Roberts of JSC. This study aims to evaluate advanced propulsion methods that might yield substantial benefits over conventional chemical propulsion for the transportation of materials between LEO and the Moon.

We have set ourselves three major tasks: To identify the most promising transportation "configurations" incorporating advanced propulsion technologies, either one at a time or in combinations; to make engineering analyses of these configurations leading to their conceptual definition, and to identify problems and R & D needs; and to develop and apply a method for evaluating the performance of the selected configurations relative to some standard reference configuration, and for a standardized mission.

The standard reference configuration employs an aerobrake-carrying, liquid  $O_2$  -  $H_2$  - propelled OTV between LEO and equatorial low lunar orbit, and a similarly-propelled lunar lander between LLO and the lunar surface. All other configurations are obtained by replacing portions of the reference configuration with advanced-technology subsystems. The advanced configurations selected up to now include several involving spinning or hanging tethers in LEO or LLO; one incorporating an ion-engine-propelled vehicle; one using a mass driver for launching loads from the lunar surface; and one employing laser propulsion for the LEO-LLO leg.

The following ground rules were adopted for the evaluation of all configurations:

- 1) The standardized mission is confined to the steady-state transport of *materials* (not people) up and down between LEO and the Moon. The objective is to deposit a fixed yearly quantity of lunar material (100, 500 or 2,500 metric tons) in LEO.
- 2) It is assumed that liquid oxygen (LLOX) is available from a processing plant on the lunar surface, but that needed liquid hydrogen comes from Earth. The LLOX is used as needed by each configuration to carry out the standardized mission, and the LLOX plant is sized accordingly.
- 3) Transport from the surface of the Earth to LEO is not considered, but the cost of transport per unit mass between these two nodes is assigned some parametric value, and all other costs are expressed in terms of this value, insofar as possible.

Two models are used to evaluate the performance of the advanced configurations relative to the reference case : a Transportation Model (TM) and an Evaluation Model (EM). The TM (described in a following paper) supplies inputs for the EM such as the payload delivered to LEO by each sortie, the amount of propellant required and hence the capacity needed for the LLOX plant, and the mass payback ratio (MPR).

The EM, formatted as a spreadsheet, has the broad features of a conventional financial model, in which the additional capital investments (relative to the reference case) needed for a given advanced configuration are traded off against its operating and maintenance savings (relative to the reference case) over a life cycle. As the bottom line, one then calculates a payback period or return on investment.

Three major novel features are incorporated into the EM. First, the capital cost includes not only the acquisition cost of each component, but also the cost of putting it in place in its proper location. Second, an attempt is made to quantify the maturity of each technology, and to take its development cost and time into account quantitatively. Third, risk of failure and need for repair are also included quantitatively in the model. The inputs for the last two features were developed with the help of panels of experts that met in workshops in July 1987.

The EM has enough fine structure to identify components or operations which are particularly costly, thereby pointing to research and development needed to bring down these costs. Its format is also convenient for sensitivity analysis with respect to various parameters, such as scale of operations, dollar equivalent of unit mass transported from Earth to LEO, interest rate, etc. Results for various configurations and parameter values will be presented.



LUNAR HISTORICAL PARKS; Philip J. Stooke, Dept. of Geography, University of Victoria, Box 1700, Victoria, B.C., Canada V8W 2Y2

A hiatus of over a decade separates the first phase of lunar exploration (up to Luna 24 in 1976) from any future missions. Extensive regolith mining is required for most lunar resource developments now being discussed. I propose that every lunar site associated with the initial exploratory period should be protected from disturbance during future lunar activities. This will preserve important historic sites for future generations, and will permit long-term studies of disturbed soil surfaces and engineering material degradation (currently possible in the lunar environment only for Surveyor III parts over a 34 month period). A system of lunar historic parks should be created for this purpose (in addition to any scientific or scenic parks that may be required). It is important to minimize the total protected area, in order not to inhibit the crucially important development of lunar resources. An international body such as the UN or IAU should soon begin to develop guidelines for these parks. National bodies such as NASM are not recommended because of the international nature of past exploration. Some preliminary guidelines are suggested here:

- (1) All impact and landing sites from the first era of lunar exploration (1959-1976) should be protected.
- (2) Parks should place minimum restrictions on future operations, consistent with (1).
- (3) Protected areas should extend to the horizon from each site. Impact sites (Luna 2 and Rangers 7-9 excepted) are of lesser priority and could be accommodated in smaller parks.
- (4) Precisely located sites in level areas (e.g. Apollo 11): minimum park boundary is a c. 3 km radius circle.
- (5) Precisely located sites in rugged areas (e.g. Lunokhod 2) should be protected out to the major ridge crests visible from the site. Minimum park boundary is a polygon linking those peaks.
- (6) Approximately located sites (e.g. Surveyor 4, Luna 2) should be surrounded by large temporary reserves (size depending on accuracy of estimated location) until precisely located, when guidelines 4 and 5 will apply. Areas needed for development and found by orbital survey NOT to include the site can be removed from the reserve. The subdivision into large and small circular reserves, used below, is for convenience only. Various sizes and shapes of reserve may be required.

These guidelines will effectively remove from possible mining or other activities only a minute fraction of the lunar surface. The protection envisaged here would preclude settlement, mining, waste disposal, surface transportation and power transmission routes, deorbiting of unwanted hardware, and impact of material during testing of mass drivers. Geological, historical or engineering research would be permitted. Hardware would ideally be left in place as historic monuments, not removed to terrestrial museums, and no hardware should be examined without permission of the government of the nation which built it. Limited surface tourism might be allowed but should be carefully monitored. In the future, similar guidelines may be applicable to Mars, Phobos and Deimos.

#### ESTIMATED AREAS TO BE PROTECTED:

PRECISELY LOCATED, level terrain: Rangers 7,8,9; Surveyors 1,6 (Surveyor 3 is included with Apollo 12); Apollos 11, 12, 13 (SIVB), 14 (SIVB, LM). Total area c. 300 sq. km (each c. 30 sq. km).

PRECISELY LOCATED, rugged terrain [areas in sq. km]: Surveyor 7 [250]; Apollos 14 [75], 15 [600], 16 [400], 17 [600]; Lunokhod 2 [600]. Total area c. 2525 sq. km.

APPROXIMATELY LOCATED temporary reserve, 100 km radius: Lunas 2, 5, 7; Ranger 4; Lunar Orbiter 1, 2, 3, 5 (Orbiter 4 site is unknown). Total area c. 240,000 sq. km (each c. 30,000 sq. km).

APPROXIMATELY LOCATED temporary reserve, 10 km radius: Lunas 8, 9, 13, 15, 16, 17, 18, 20, 23, 24; Ranger 6; Surveyors 2, 4, 5; Apollos 12 (LM), 15 (SIVB, LM), 16 (SIVB), 17 (SIVB) (Apollo 17 LM is included in landing site park). Total area c. 6,000 sq. km (each c. 300 sq. km).

TOTAL AREA: c. 250,000 sq. km., or 0.6 per cent of the lunar surface. This can be reduced as large reserves are replaced with small parks. The final total will probably not exceed 10,000 sq. km, about 0.03 per cent of the lunar surface. Note that a few additional impact sites remain to be identified, particularly of crashed orbiters.

## OCCUPATIONAL ERGONOMICS IN SPACE

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A significant amount of work has been done on earth toward understanding man's physical capabilities in the working environment. Little work has been done toward understanding how well man will be able to perform work in zero-g or on the Moon or Mars, which are the two most likely candidates for manned exploration in the foreseeable future of man's explorations of space.

Some insight can be gained from the Apollo program. Astronauts performed some lifting, bending, and other tasks on the moon. However, no provision for systematic study was done on these activities. As a result, we know very little about the limits of man's work capacity on the moon.

This paper provides a review of previous work in the area and discusses some possible test methodologies using earth-based testing for determining man's lifting and other capabilities on the moon and elsewhere.

Before the equipment is designed and tasks developed, consideration must be given to man's capabilities across a range of g forces and the effects of possible recent prolonged periods of microgravity. Should this not be done, an astronaut might arrive on Mars expected to perform some task which is physically impossible. This consideration must necessarily include both suited and unsuited activities, since it is expected that people will work both inside and outside the structures built there.

**CONCEPTUAL DESIGN OF A LUNAR LANDER;** W.R. Stump, C.C. Varner, C. Blacknall, O.G. Morris, C.W. Yodzis, and R.P. Rawlings, Eagle Engineering Inc., 711 Bay Area Blvd., Suite 315, Webster, Texas 77598. J.M. Stecklein, A.J. Petro, NASA Johnson Space Center, Houston 77058.

The purpose of this study was to evaluate and conceptually design a reusable, single stage lunar lander capable of landing a crew on the lunar surface or cargo on the order of 25 metric tons. A comparison with a two stage design was performed. Trade studies were conducted to select a baseline parking orbit altitude, inclination, propellant loading and maintenance location, propellant and engine type and number, and required maintenance.

Subsystem studies were conducted to define in some detail the main engines, attitude thruster system, guidance, navigation, and control system, life support system, and electrical power system. A weight statement for the baseline lander and several variations of it was produced. Cost was also addressed. Conceptual design drawings and an airbrush illustration were produced. A annotated bibliography of most previous lander work is also included.

## CELSS and Energy systems of Lunar Base

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A closed ecological life support system (CELSS) and Energy systems are important technologies to maintain for semipermanent Lunar Bases.

This paper proposes a method that enables CELSS to utilize sunlight directly and energy systems designed around new technologies now under development.

- (1) With the exception of plant horticulture factories, all CELSS processes are currently operated by electricity. It should be possible for these systems to utilize sunlight more effectively. The energy supply methods now used in CELSS are not very economical, because the electrical capacity obtained with solar battery panels is small.

CELSS can make direct use of sunlight for three main operations : plant photosynthesis, illumination and disinfection of animals and treatment of excrement. Instead of using electrical energy, the CELSS proposed here can provide energy for all three operations with only one sunlight equipment unit.

- (2) The proposed energy supply system uses solar energy as it's main energy source. It has so far not been suitable for semipermanent Lunar Bases because of two main drawbacks. One is that the long intervals of day and night on the moon would make it impossible for a solar energy system to provide sufficient energy at night. The second problem is that solar batteries are inefficient at generating electricity.

These problems are expected to be solved by technologies now being developed. Superconductive storage systems should overcome the storage and supply drawbacks. Hybrid solar batteries should improve the power generation efficiency.

- (3) The proposed heat balance system provides an effective method where by low-temperature heat energy generated in the course of everyday life in Lunar Bases can be recovered and used for other purposes. Super heatpumps and highly efficient energy accumulation and storage systems will make it possible to use such low-temperature heat energy, which cannot be utilized at present.

This energy can be used in factories and in low-temperature power generation.

**SITE SELECTION CRITERIA FOR ASTRONOMICAL OBSERVATORIES ON THE MOON.**

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The Moon's tenuous atmosphere, seismic stability, and, on the farside, low radio background make it an ideal location for observatories. To take full advantage of it when a lunar base is established, we must develop criteria to use in selecting appropriate sites. We report here a preliminary assessment of siting criteria for three types of telescopes: a Very-Low Frequency (VLF) radio array, Moon-Earth Radio Interferometer, and an Optical/Infrared Interferometer. As telescope designs become better defined criteria for selecting sites will become more quantitative.

**Longitude:** The VLF array needs to be located on the farside of the Moon to shield it from terrestrial interference, especially from that generated in the ionosphere. How far it must be from a limb needs to be calculated because radio waves are diffracted by the Moon. The other telescopes could be located on the nearside.

**Topography:** Rugged topography is incompatible with the installation of a long-baseline array, so both the VLF and optical/infrared facilities will require relatively flat areas. Precisely how great a relief difference can be accommodated needs to be determined. The maria are obvious first choices, though these are rare on the farside. Possibilities include Mare Ingenii (35°S, 165°E), Mare Moscoviense (25°N, 145°E), and the large crater Tsiolkovsky (20°S, 130°E). All are large enough to contain an array larger than the 30 km required for an ambitious VLF observatory. There are also relatively flat areas formed by deposits of impact-melted materials, such as the 15 x 15 km pond outside of King Crater (5°N, 120°E); most are probably too small for the VLF array, but could easily accommodate the optical array, which would probably be less than 10 km across. It might also be possible to use areas covered with relatively smooth impact deposits, such as the Cayley Formation.

**Distance from lunar base:** Besides logistics (transportation, etc.), the distance an observatory needs to be from an active lunar base, especially from mining and processing operations, depends on several environmental factors. The first is seismic vibrations generated by mining operations and spacecraft landings and liftoffs. These will certainly increase the lunar seismic background, but whether they will render alignment of arrays less accurate remains to be assessed. Second, dust will be distributed by spacecraft operations, which could coat telescope surfaces, leading to increased maintenance and possibly permanent damage. Third, base operations will inevitably lead to the release of gases into the lunar atmosphere; this could lead to local, if not global, effects that could interfere with astronomical observations.

**Value to lunar science:** All things being equal, it is logical to choose a site of geologic interest, which could be studied intensely during the time the observatory is being constructed, with follow-up studies whenever visits must be made for maintenance.

**Value as a materials resource:** Mining and astronomy are incompatible on the Moon, so sites that hold obvious resource potential must be avoided.



**MANTLE SAMPLES AND THE BULK LUNAR COMPOSITION: CONSTRAINTS ON THE ORIGIN OF THE MOON.** Lawrence A. TAYLOR and Clive R. NEAL: Department of Geological Sciences, The University of Tennessee, Knoxville, TN 37996-1410.

Principle amongst the parameters concerning the origin of the Moon are the compositions of the mantle and the bulk Moon. These are compared with Earth analogs and are paramount in addressing the nature of the proto-lunar projectile for the most popular theory, that of collisional ejection [1]. The Lunar Geoscience Orbiter project will better constrain the crustal composition of the Moon [2], but LGO will give no direct evidence as to the composition of the lunar interior. As yet, no unequivocal samples of the lunar mantle have been returned. Instead, the nature of the mantle has been inferred based upon its presumed origin in connection with the crust. Attempts have been made at calculating the bulk composition of the Moon using: a) a mean highland composition; b) an assumed thickness for the crust; and c) an assumed composition for the mantle, the largest portion of the moon (80-90 vol%). It is obvious that critical to the determination of the bulk Moon composition is the nature of its mantle. We need samples of the mantle. Such samples also may yield evidence which addresses the magma ocean hypothesis and the source region of the mare basalts.

The establishment of a lunar base would facilitate field excursions in search of elusive mantle samples. Geophysical and experimental evidence indicates that the upper mantle of the moon is predominantly composed of olivine and pyroxene [e.g., 3 & 4] with garnet stability below  $\approx 400\text{km}$  [3]. However, **where would we search for pristine lunar mantle material?** Suitable areas would be where there has been crustal thinning and mantle upwelling. Large impact craters where the crust has been deeply excavated often have large gravity anomalies and frequently contain central uplift peaks. These are considered to be areas where mantle material has rebounded nearer to the surface. Large, young impacts are the best bet to have excavated down to the mantle and still contain samples from depth which have not been reworked and comminuted by later meteorite bombardment. Craters such as Copernicus have central Mg-rich regions (determined by spectral reflectance; [5]) which should be examined in detail for mantle samples. Such fresh craters may contain layers retaining some of the local stratigraphy. With enhanced gravity and spectral reflectance determinations (conducted by the LGO which will proceed the establishment of a lunar base), it should be possible to locate several craters where probable mantle material is unusually close to and/or at the surface. These would undoubtedly be some of the most valuable places to conduct both field work and drilling programs.

On the Earth, we obtain samples of our mantle from two sources: 1) diamondiferous rocks, such as kimberlites, and 2) certain alkali basalts, which contain mantle xenoliths. A source of primary mantle material on the Moon may be in recent lava flows which could be searched for mantle xenoliths. With lower gravity on the Moon, it is certainly feasible that mantle-derived material was rafted up and preserved in certain basalt flows.

The benefits of these endeavors will be to accurately determine the nature of the mantle and thus, the bulk composition of the Moon. As a bonus, evidence for certain ore mineral accumulations, such as occur in layered chromite deposits [6], also may be discovered.

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A LUNAR BASE INFORMATION SYSTEM; S. H. Tellier & F. B. Waranius,  
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Based on experience during and after the Apollo Program, it is vitally important to have a central location where material and information relating to a special project, such as Lunar Base, can be archived. At this location all pertinent items can be collected, organized and made available to the interested parties. This approach helps to insure that researchers have the most complete and up-to-date information available. It also will lessen pressure on limited resources by reducing duplication of effort. This system could provide; a history of the project and other background information, an exchange point for messages and information, meeting announcements, a calendar of events, contact information, project descriptions and work-in-progress, and more.

Given today's computer networking capabilities, it is possible for such an information system to have an even greater impact on a project. It could act as a gateway to other resources that already exist on computers at other locations and in a manner totally transparent to users. In addition, information and other resources could be delivered, in effect, to a researcher's desk for immediate inclusion in on-going work. Future applications could expand the capabilities to allow users to interact with other systems, databases, computer models, etc. The services could become an integral part of developing a base on the Moon. Ultimately the system could be the basis for the information system at the Lunar Base itself.

Thus, we propose, with the cooperation of the Data Center, Planetary Materials Branch, Johnson Space Center, to establish a Lunar Base Information System at the Lunar & Planetary Institute. Access to this system will be possible from virtually any remote location via computer networks such as SPAN or with a modem and telephone. The central focus of this system will be a computer-searchable bibliographic database of documents, articles, and other items pertaining to the establishment and use of a lunar base. The core of this database will be material generated during the Apollo Program and other information already located at the LPI. Additional items will be solicited from organizations, contractors and individuals working on Lunar Base projects to keep the database current. These materials will be maintained at the Institute and will be available for review, photocopying, borrowing or distribution by electronic means, depending on equipment available and the nature of the material.

Consideration of this proposal is important now because the time to collect and catalog this information is now, at the point of production. Most often the planning materials, documents, drawings, meeting minutes, etc., which contain a great deal of valuable information, are soon "lost" in the "grey literature" after the initial distribution is made.

Present plans include a demonstration of a prototype information system at the symposium in addition to a paper describing it in greater detail.

## NUCLEAR POWER APPLICATIONS FOR LUNAR AND CISLUNAR MISSIONS

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Under the sponsorship of Johnson Space Center (JSC) and the Universities Space Research Associates (USRA), the Department of Nuclear Engineering at Texas A&M University has been heavily involved in the design and development of a wide range of space nuclear power systems. This effort has been underway for approximately 4 years. Many of the results from this effort can be directly applied to lunar and cislunar missions. These applications include; propulsion for craft operating between earth orbit and lunar bases or between these bases and other stations such as a Mars base or asteroid mining post, electrical power for life support and communications, and thermal power for materials processing. Some example design topics are presented below.

A generic issue in any space program is propulsion. Accordingly, a large amount of the design effort in this program has been directed at propulsion systems. Nuclear reactors have been designed for direct nuclear (thermal) and electrical (ion and magnetoplasmadynamic) propulsion. Propulsion designs must be developed in conjunction with a lunar base for the exchange of personnel, supplies and raw materials between Earth and the lunar base and from this base to other posts in the solar system or beyond.

A number of designs have been focused on the development of Mars based systems capable of delivering large amounts of electrical and thermal power (in excess of 1 megawatt) for life support and materials processing. The experience gained in these designs can be directly applied to the development of large power sources for lunar bases. A recent design effort was focused on the development of a subcritical assembly power source to serve as an alternative to plutonium (Pu) bearing radioisotope thermal generators (RTG's).

The Aerospace Department at Texas A&M has been involved in design activities applicable to lunar base development as part of the work sponsored by USRA and JSC. Their efforts have been primarily directed at space craft trajectory analysis, space craft design, and deployment procedures for and design of base structures. The resources of other engineering and science departments within the Texas A&M system have also been utilized as part of the overall effort to develop system designs relating to space exploration and colonization.

In summary, an extremely active program for the development of space nuclear power systems has been established and a wide range of design concepts have been investigated. Much of this effort can be directly applied to the development of systems for the support and operation of lunar bases.

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The goal of the study described here is to design a Solar Power Satellite (SPS) system for optimal use of lunar resources, which could reduce the cost of transporting materials to geosynchronous orbit. Use of lunar resources for SPS construction has been studied previously, (1) but that work allowed only minor changes to an earlier design (2) which used Earth materials.

The design described here uses existing technology as much as possible to improve commercial feasibility.

It was found that an SPS can be designed which uses less than one percent as much non-lunar material as the Earth baseline SPS, a factor of ten improvement over the previous study. (1) Total mass of the system is about eight percent greater than for one made from Earth-derived materials. The best design uses silicon photovoltaic cells for power conversion. Its structure is primarily aluminum and uses aluminum oxide coatings for thermal control. A flywheel system is used for energy storage during eclipses. The design is suitable for largely automated construction.

An alternative design uses gallium arsenide cells with solar concentrators. This roughly triples total SPS mass, but non-lunar mass remains less than two percent of that for the Earth baseline. Four other power conversion systems were investigated: thermophotovoltaic (TPV), Brayton, Rankine, and Stirling. These used significantly more non-lunar material than either the silicon system or the gallium arsenide system.

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INTERNATIONAL LAW AND LUNAR EXPLORATION: DEFUSING THE  
SOCIALIST CHALLENGE; Paul F. Uhler, National Research Council

National and international space law regarding the exploration and use of the Moon is currently inchoate. A concerted attempt to fill this legal vacuum with a regime based on "socialist" norms is being mounted at the United Nations by the Soviet bloc and 3d World countries. They seek to stifle our democratic values and free enterprise principles during the formative stages of international space law.

Although the Soviet and 3d World legal positions on future lunar activities are often at variance with each other, they are unified in their opposition to the Western legal model. Soviet international law generally, and space law specifically, is rooted in Marxist-Leninist theory. Soviet jurists endeavor to restructure the international law system on a "socialist" (Soviet) basis. Since space law is largely undeveloped, the Soviets see a significant opportunity for influencing its evolution. Their vigorous space program will ensure an important precedent-setting capability that they are certain to exploit if the United States and our democratic allies do not meet the challenge.

The 3d World (Group of 77) nations perceive outer space exploration as a global entitlements program. Their rallying point is the Moon Treaty, which incorporates some heavy ideological baggage from the 3d Law of the Sea Conference (UNCLOS III), and from their advocacy of a New International Economic Order and New World Information Order. Despite the generally ill-founded substance of their legal arguments and their inability to set precedents in practice, the 3d World position should not be taken lightly given their numerical superiority at the United Nations and other international fora.

It is therefore essential that the United States emphatically repudiate these negative influences on the emerging legal regime and, at the same time, develop not only a positive legal theory for our future lunar activities, but maintain a strong and effective program of our own.



USES OF LUNAR SULFUR; D. Vaniman, D. Pettit\*, and G. Heiken, MS D462 (\*MS P952), Los Alamos National Laboratory, Los Alamos, New Mexico, 87545.

Although volatile constituents ( $H_2O$ ,  $CO_2$ , etc.) are generally depleted in lunar rocks, sulfur is abundant in some mare basalts. High-Ti mare basalts have S contents in the range of 0.16% to 0.27% by weight; on Earth basalts with more than 0.15% S are very rare [1]. Sulfur is correspondingly abundant in high-Ti mare soils. Although admixture and volatilization reduce the S content of high-Ti soils to about 0.06–0.13% [1], S in lunar soils is easily extracted. Heating to  $950^\circ C$  releases 50–70% of the soil S, and 85–95% is extracted at  $1100^\circ C$  [2]. High-Ti soils with an average 0.1% S content could yield ~1 metric ton of S from a patch  $100 \times 100$  m and 10 cm deep. Heating would require about 0.1 Mw/metric ton of S/year (100% duty cycle). Alternatively, in a lunar  $O_2$  production scheme which also requires high-Ti soil [3], byproduct sulfur would be at least 1% of the  $O_2$  mass produced and as much as 10% of the  $O_2$  mass if the slag is also heated. In the  $O_2$  production plants envisaged [e.g. 3], the S byproduct could be about 10 to 100 metric tons per year. Co-generation of S could be very important for the uses outlined below.

1) Use of S fluid properties: No working fluids are native to the Moon; the absence of fluids complicates many operations, ranging from hydraulic systems to solvent processes. Elemental S melts to a low-viscosity fluid at  $113$ – $119^\circ C$  (depending on crystalline state) but viscosity rises with temperature; at lunar daytime temperatures ( $\sim 107^\circ C$ ) minimal heat input would maintain S as a low-viscosity liquid. Another potential fluid is  $SO_2$ , which is used on Earth as a nonaqueous, aprotic, dipolar solvent that freezes at  $-75.5^\circ C$  and boils at  $-10.1^\circ C$  [4]. With imaginative chemical engineering, much of the costly importation of terrestrial fluids may be avoided.

2) Use of S electrical properties: Systems based on S may be used to collect solar energy and to store it as electricity. Photoelectrochemical cells using  $Na_2S$ –S–NaOH electrolyte have efficiencies  $>5\%$  [5]. Electric vehicle researchers [6] are developing commercial rechargeable batteries using a S cathode and Na anode separated by beta-aluminum (allowing passage of Na ions). Modifications of these S-based energy collection and storage systems may be very useful on the Moon; batteries in particular would use large masses of lunar materials that would not have to be lifted from Earth. Import of NaOH from Earth may be required, probably as a solid, but the stoichiometry of the S-based electrical systems would liberate much of the valuable OH from this import for other uses on the Moon.

3) Use of S chemical and biochemical properties: A "brimstone rocket" based on S–O combustion is an attractive propulsion system because it could use propellants that are solely Moon-derived. Sulfur is also important in industrial chemistry; sulfuric acid usage is a measure of industrial capacity on Earth. Sulfur may have lunar biochemical uses in plants (e.g. fertilizers) and animals; there is an extensive literature on sulphydryl compounds as ingested radioprotective agents [7]. If human presence is going to be more than transient on the Moon, sulfur may play a critical role.

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## CROP GROWTH AND ASSOCIATED LIFE SUPPORT FOR A LUNAR FARM

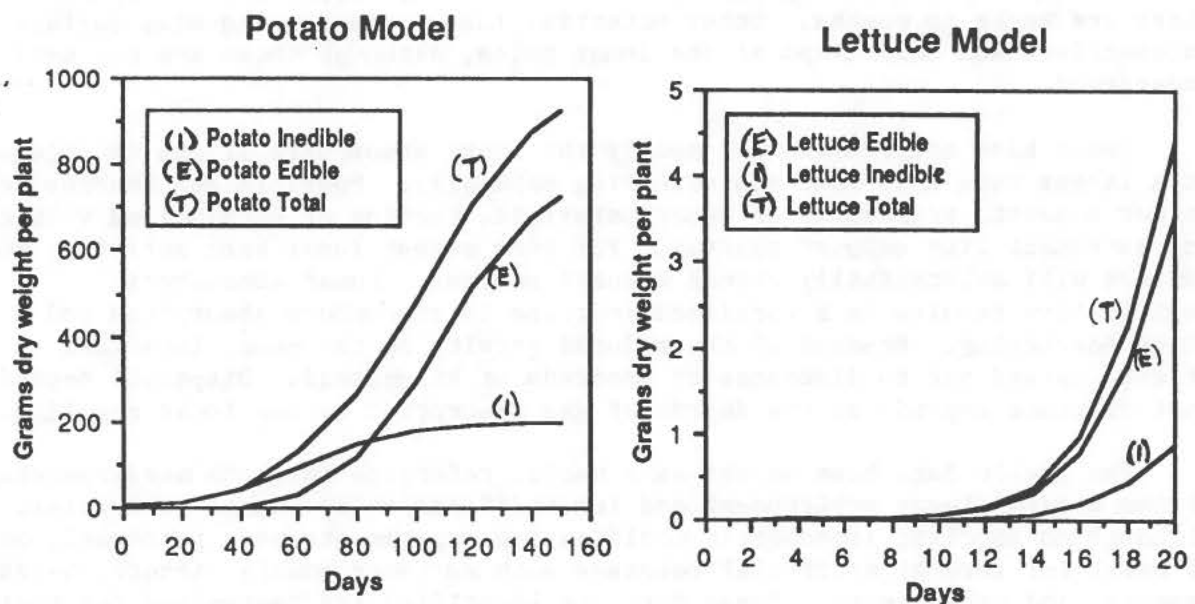
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Human life support for advanced space missions, such as the lunar and Mars bases, will require the management of many different food crops. This paper investigates the growth dynamics of four crops--wheat, soybeans, potatoes, and lettuce--for their general similarities and differences with their material flows of the gases, liquids, and solids in a lunar farm.

To simulate a lunar farm, two differential equations, one each for the inedible and edible portions of the crop's biomass, are developed and applied to the general characteristics of each crop's growth pattern. Model parameters, such as ultimate sizes and growth rates, are determined by closely approximating each crop's data. These parameters are constant here for each crop, in order to demonstrate the capability for a relatively simple generic model to reproduce the overall characteristics of growth of different crops. In actuality these parameters are functions of environmental qualities, such as photosynthetic photon flux, photoperiod and atmospheric  $p\text{CO}_2$ . This kind of modeling can aid the conceptualization of a lunar farm by providing flux rates of substances going into and leaving the plants. Flux rates for  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{HNO}_3$ , and  $\text{O}_2$  developed here are given for a lunar application.



## LUNAR BASE ACTIVITIES AND THE LUNAR ENVIRONMENT

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The moon is an attractive site for astronomical observatories because of the absence of a substantial lunar atmosphere and the stability of the lunar surface. The present lunar atmosphere is sufficiently transparent that there is no significant image distortion due to absorption or refraction. Furthermore, the absence of a significant lunar ionosphere allows the use of the moon for radio astronomy at frequencies much lower than those observable with terrestrial facilities. However, lunar base activities can significantly alter the natural lunar environment. This paper describes the physical processes that determine the characteristics of the lunar atmosphere and ionosphere. Data from the Apollo program are then used to assess the environmental modifications that can be expected from lunar base activities.

The present thin atmosphere on the moon results from a combination of small sources and prompt losses. The major source that has been identified is the solar wind, whose total mass input into the lunar atmosphere is less than 50 gm/sec. The only endogenous gases that have been identified are argon and radon, decay products of radioactive materials in the lunar interior. Although larger sources due to localized release of gases have been suggested in association with lunar transient phenomena, none have been conclusively detected.

The principal atmospheric loss mechanisms are thermal escape and solar-wind ion pickup. Thermal escape is important only for solar wind hydrogen and helium. For heavier gases the most rapid loss mechanism is photoionization followed by loss to the solar wind. Typical photoionization times are weeks to months. Other potential loss mechanisms involve surface interactions and cold traps at the lunar poles, although these are not well understood.

Lunar base activities will modify the lunar atmosphere if gas is released at a larger rate than that now occurring naturally. Possible gas sources are rocket exhaust, processing of lunar materials, venting of pressurized volumes, and astronaut life support systems. For even modest lunar base activity, such sources will substantially exceed natural sources. Lunar atmospheric modification results in a localized increase in atmosphere absorption and light scattering. Because of the reduced gravity on the moon, localized effects spread out to distances of hundreds of kilometers. Dispersal beyond that distance depends on the degree of gas absorption by the lunar regolith.

The Apollo data base serves as a useful reference for both measurements of the natural lunar environment and its modification by manned activities. Although no specific atmospheric modification experiments were performed, data do exist for several artificial releases such as Lunar Module liftoff, S-IVB impacts, and cabin vents. These data are identified and reexamined for their relevance to the assessment of lunar base alteration of the atmosphere and ionosphere.

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For return of lunar raw materials to LEO, high efficiency transportation systems are described which contain the following elements or features:

- (1) lunar surface facilities to collect and mechanically eject unconfined fine lunar soil to low altitudes (10 to 50 km)
- (2) cyclic cargo vehicles which can collect the ejected lunar soil near perilune passage and off-load the cargo in packaged form near perigee
- (3) modified free return (cyclor) trajectories for lunar-LEO cargo delivery
- (4) expendable light weight aerobraking systems to circularize cargo packages
- (5) (optionally) a lunar orbiting vehicle to perform the direct lunar soil collection and rendezvous and transfer packaged cargo to cyclic cargo vehicle as in 2)

Repetitive eccentric earth orbital trajectories are developed for return of lunar soil to earth orbits of arbitrary inclination. Required velocity changes near earth perigee are relatively low and can be accommodated by tether off-loading of payloads.

Constant energy (coasting) orbits are described suitable for transfer of large payloads brought to soft rendezvous with the transport spacecraft or for changing orbital planes.

Energy or momentum change orbits are shown which lose kinetic energy or momentum near the moon and restore it near earth perigee. The transport energy requirements are less than 5 percent of those needed for direct lunar escape and less than 0.3 percent of earth surface to LEO transport.

LUNAR MANUFACTURING: A SURVEY OF PRODUCTS AND PROCESSES

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A survey of materials processing systems compatible with accessible input fractions of lunar materials is presented. Initial processing steps can be divided into three groups:

- (1) reagentless
- (2) requiring reagents composed solely of lunar recoverable elements
- (3) requiring reagents containing some earth imported elements.

The capabilities and constraints of the processes are discussed and a range of output materials, products and potential applications derivable solely or predominantly from whole sample separation and refinement systems is outlined.

Processing systems containing steps of the third class above must include reagent regeneration steps to produce quasi-closed-cycle loops for all lunar deficient elements. Primary factors affecting the attrition rates of reagents containing lunar deficient elements are described.



LUNAR PROCESSING OPTIONS FOR  
LIQUEFACTION AND STORAGE OF CRYOGENS

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Oxygen for propellant or fuel cell use may be generated from lunar raw materials by one or more processes at temperatures and pressures which could encompass a broad range of values. High temperature systems such as magma electrolysis or thermal dissociation of transition metal oxides will normally yield oxygen at temperatures of 1500°K or higher at low to moderate pressures while aqueous electrolysis yields the gas at moderate to high pressures and temperatures below 400°K.

Methods of cooling and compressing oxygen may take advantage of thermal management systems unique to the lunar environment. A system for liquefying oxygen without mechanical compression from a 30 atm flowline derived from aqueous electrolyzers will be described.

For processing loops using mechanical compressors, reliability concerns favor operating compressors between about 250° and 600°K. Recommended liquefaction process cycles for oxygen derived from high temperature processes will be outlined. Improved methods for passive radiant cooling useful for liquid oxygen storage on the lunar surface are presented.

Practical hydrogen liquefaction and storage cycles require heat rejection at the lowest possible temperatures, preferably below 140°K. Useful cycles are described which use combinations of lunar daylight, geometrically shielded radiant cooling and/or cold storage provided by lunar night, radiation-cooled lunar soils.

POWER SYSTEM PLANNING FOR A SUSTAINED LUNAR BASE

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The goal of this paper is to identify and evaluate the key attributes and issues for optimizing a space power system configuration for a sustained lunar base from an energy/load management perspective. To achieve this objective, a range of assumptions will be made on the nature of the lunar base's development: initial, intermediate, and final power consumptions; distributed and or central distribution and transmission systems; percent of manned versus unmanned outposts; and the degree of autonomous versus manual control of overall power system. Some of the attributes to be evaluated will include, but not be limited to, overall implementation costs, size, and weight.

This paper will accomplish its objective by applying traditional terrestrial power system planning techniques to power system planning for lunar colonies.

MAINTENANCE AND REPAIR: A CRITICAL ELEMENT OF LUNAR  
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Because of the remoteness from Earth, a lunar base and associated activities (eg. mining, materials processing, space science research) must be largely self-sufficient. Therefore, a critical aspect of lunar base operations will be maintenance and repair capabilities.

Formal planning of maintenance and repair requirements cannot begin until preliminary design of the lunar base elements is initiated. At that point it will be appropriate to apply established evaluation methods such as the failure modes and effects analysis (FMEA) [1], reliability analyses [2,3], and maintainability analyses [4] to define specific technology requirements.

Prior to that, however, it is possible to assess the potential magnitude of lunar base resources which will be consumed by maintenance and repair activities, as well as the technical capabilities which will be necessary, through analogy with earlier space missions and applicable terrestrial operations. Experience with Skylab and the Soviet orbiting laboratories has shown that in-flight maintenance is essential [5]. In terrestrial mining maintenance and repair, particularly to combat the effects of wear, is a significant factor in mine operation. Submarines and polar research stations are further examples of terrestrial systems which are analogous to planned lunar bases by virtue of their inaccessibility to support facilities and the subsequent requirement for nearly autonomous operation.

Early development of guidelines from this experience will be invaluable to assuring the most productive application of limited resources to the development of essential technology.

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- [3] Reliability program Requirements for Space and Missile Systems. MIL-STD-1543, (July 22, 1977).
- [4] Maintainability Program Requirements for Systems and Equipment. MIL-STD-470, (March 29, 1966).
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## CONSTRUCTION OF AN UNDERGROUND LUNAR BASE

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Initial lunar base construction will most likely consist of burying space station modules. In an effort to achieve self sufficiency, more space will be required. For purposes such as equipment maintenance, food production, full scale ore processing, drill chamber-core sampling, stockpiling of lunar and astronomical research equipment, the stockpiling of medical supplies, more importantly a well equipped medical facility<sup>1</sup>, the use of space station modules will no longer be adequate.

The excavation of underground space provides an attractive option. At only "tens of meters" the temperature is a constant 20°C<sup>2</sup> and enough shielding from lunar surface hazards such as radiation and micrometeorites is provided. The facilities can be made to a variety of configurations and finished as necessary.

This paper reviews sub-selene construction technology options and their desirability as determined by economic factors. Specifically, development and shipping costs, and man-hours required for construction. Methods of sealing the tunnel sides as well as access airlocks will also be considered in this evaluation.

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<sup>1</sup>Logan, James, M.D. Personal Communication. May 6, 1987.

<sup>2</sup>Horz, Friedrich. "LUNAR BASES AND SPACE ACTIVITIES OF THE 21st CENTURY." pp. 405-412. 1984.

### **The Impact to the Space Station of Manned Lunar and Mars Initiatives**

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The manned Lunar Base and Mars mission initiatives being considered will severely impact the Space Station (SS) and the transportation infrastructure required to support it. Previous studies (e.g., (1)) have concluded that the SS is capable of supporting these manned missions. However, only cursory attention was given to the associated transportation infrastructure, SS mass properties, and the additional station personnel required to support these initiatives. In particular, no consideration was given to the impact on other station users of these aggressive manned programs. Detailed studies have illustrated the need for a transportation hub separate from the SS. Three different manned mission scenarios are examined: 1. Permanently manned lunar base, 2. Manned Mars mission from LEO, and 3. Lunar base as a precursor to a manned Mars mission.

The impact of a permanently manned Lunar Base on the SS involves an evolution of the station into a transportation node for transferring people, equipment, supplies, and lunar materials to and from LEO and the lunar surface. Manpower required at the station increases significantly as lunar exploration evolves from unmanned precursor missions to a fully operational lunar base. Large mass variations at the station on a repetitive lunar launch cycle result in violations of microgravity restrictions. Continual STS, heavy-lift launch vehicle, and orbital transfer vehicle arrivals and departures degrade Earth observations and astrophysics experiments due to contamination. Similarly, station-resident propellant tank farms and lunar vehicle assembly hangars restrict fields of view.

A manned mission to Mars requires the station personnel to concentrate much of their efforts on evaluating closed-loop life support systems and the life-science implications to humans of long-duration exposure to zero gravity and the space environment. Building the Mars vehicle will result in large station c.g. translations and significant degradation in Earth observation capabilities while the vehicle is attached to the station. The station must be capable of storing and transferring very large amounts of propellant (1-2 million pounds) and supporting the increased crew needed to operate and construct the required facilities and perform the life-sciences research.

The implications for the SS of a mission to Mars following the establishment of a Lunar Base depends on where the Mars vehicle is launched from and built. Launching the Mars vehicle from LEO, using lunar oxygen, does little to reduce the impact of the Mars mission on the SS. In fact, the SS will have to support both the Lunar Base and the Mars initiatives simultaneously, with the combined impacts of these missions affecting the other SS users. If the Mars vehicle is assembled and launched from a transportation node at a libration point (L1), the vehicle size and required propellant for the mission can be substantially reduced, placing less demands on the Lunar Base and eliminating many of the problems for the SS. The SS must still process vehicles from Earth and send them to the L1 Station. However, the mass flow through the SS is greatly reduced.

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CHARACTERISTICS OF A SIMULANT FOR LUNAR SURFACE MATERIALS. P. W. Weiblen and K. Gordon, Department of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55455

A simulant for lunar mare materials (LMM), Minnesota Lunar Simulant #1, (MLS-1), can now be provided to the lunar base community with characterization and processing appropriate to its use. No single simulant can meet all the needs of the diverse research that is essential to an effective lunar base program. However, a simulant that meets certain basic criteria, if used in different research projects will minimize the number of floating parameters in the research. We have initiated an effort to provide a simulant for **lunar mare materials** based on the following criteria: 1) The simulant should match as close as possible the chemistry, mineralogy, and texture of a **specific** lunar material. 2) The original rock should be as homogenous as possible from an accessible site with a well-defined geologic setting. 3) Processing of the material should be carried out with documented, reproducible methods. 4) Characterization of the simulant should be ongoing and iterative - extending the data base in concert with the research in which it is used. The extent to which MLS-1 meets these four criteria is summarized below.

1) *Match with lunar materials* - Chemically, MLS-1 and LMM are quite similar (Fig. 1); however, MLS-1 contains 3.5 wt. % ferric iron and 0.4 water (1) which are not present in lunar material. MLS-1 differs from typical mare basalts in its higher feldspar content, the presence of a few % biotite and ferric iron in the Fe-Mg minerals. The ubiquitous glass and mineral fragment agglutinates produced by meteorite impact processes in LMM are absent in MLS-1. The texture of mineral grains in MLS-1 is more blocky than the typically acicular quench texture of most lunar mare basalts.

2) *Geologic setting, accessibility, and homogeneity* - A 1000 kg sample of MLS-1 was obtained from a one to two meter thick basalt sill that extends about 50 meters across a rock face of an abandoned quarry within the City of Duluth, MN. The sill intrudes anorthositic rocks of the Duluth Complex (2). Average grain size increases slightly from 0.05 to .01 mm away from the sill contact. However, the variation in mineral proportions and bulk chemistry across the exposure is minimal.

3) *Processing* - Sample MLS-1 was crushed, ground, and sieved under reproducible conditions in the sample processing facilities of the Mineral Resources Research Center (MRRC) at the U. of Minn. Glass resembling lunar agglutinates has been produced from MLS-1 in a plasma torch facility at MRRC. Mixtures of the glass and MLS-1 can simulate lunar regolith sample 10084 (4) quite closely (Fig. 1).

4) *Characterization* - The geologic setting, petrography, petrology, and geochemistry of MLS-1 are being studied in a thesis project (K. Gordon). Samples of MLS-1 are being used in plant growth experiments in the laboratories of the LAND, Epcot Center. Data being obtained on the products from the soil forming studies will add to the data base on the physical and chemical properties of MLS-1.

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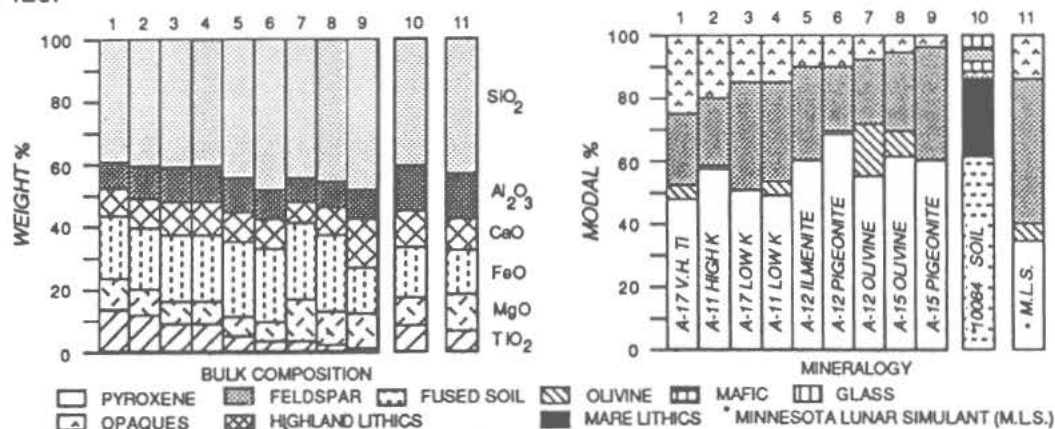


Fig. 1. Comparison of mare basalts, mare soil 10084, and MLS-1. Modified from (3 & 4).

STUDY OF THE USE OF THE SPACE STATION TO ACCOMMODATE LUNAR BASE MISSIONS; DR. D. J. WEIDMAN, NASA LANGLEY RESEARCH CENTER, MAIL STOP 288, HAMPTON, VA 23665; W. CIRILLO, PRC-KENTRON, MAIL STOP 288, HAMPTON, VA 23665; C. P. LLEWELLYN, SELF CORPORATION, GRAFTON, VA 23692

NASA Langley Research Center was requested to evaluate the effect on the planned Space Station of accommodating the series of missions required to build and sustain a lunar base. This study was conducted in the second quarter of 1987 and included participants from several NASA Centers and contractual support. The study included review and selection of the mission components or elements, definition of the means of assembly, and evaluation of the support activities required for continued maintenance of both the space and surface infrastructures.

The main thrust of the study was the definition of scientific and technology needs to accomplish the lunar base assembly and support activities through use of the station without losing the scientific projects already planned for the station. Also, the station and lunar elements were specified, and their impacts on the launch requirements from the Cape were determined.

The large logistics and fuel transfer activities were found to be important and were quantified, and their impact on space operations were reviewed. Results indicate that the lunar missions require the development and use of Heavy Lift Launch Vehicles (HLLV). Some trade studies were conducted and assessment of options were made.

The station was found to have the ability to handle the large transfer of elements and the fuel requirements without major redesign or alteration, but some additional structures were needed, such as a fuel facility for handling the massive amounts of LH2/LOX needed for transport to and return from lunar orbit. The crew workloads were of some concern, especially with the refurbishment of lunar vehicles. The general design of the Space Station as a dual keel was sufficient to accommodate all needed activities, and provides further confidence in the utility of the basic design.

A summary of vehicle and Space Station elements and their sizes and masses are included in the report and are important to researchers working on studies of lunar missions.

LUNAR-BASED CONSTRUCTION SYSTEM, J.H. Wickman and E. James, Wickman Spacecraft & Propulsion Company, Citrus Heights, California 95621

The economical construction of a space station in orbit about the earth and in the vicinity of the moon poses a major technical problem. One of the reasons is the cost of launching all the building and construction materials from earth to the construction site in space. The Lunar-based Construction System reduces the dependence on earth for construction supplies. The system consists of three major subsystems: (1) lunar-based concrete production/mixing, (2) lunar-based propulsion/vehicles and (3) a robotic astronaut for assembly of the station in space. Since the Lunar-based Construction System primarily travels only between earth orbit and the moon, it opens the possibility of economical construction of a GEO space station. The inflatable concrete construction techniques could also be used in the construction of a lunar base.

The Lunar-based Construction System uses lunar soil for the concrete. If water for the concrete can be found in space or on the moon, then it would not need to be supplied from earth. If water is not found, then it can be manufactured in space or on the moon by supplying hydrogen from earth and combining it with the oxygen already available in the lunar soil. Another possibility is to use microwave energy to bake the lunar material in the inflatable forms to form a hard shell. This eliminates the need for water.

The lunar concrete materials are transported to the construction site by a spacecraft powered by lunar-based propulsion. The propulsion system uses lunar oxygen with a lunar fuel such as aluminum, magnesium, iron, sulfur or phosphorus (1). The lunar material is mixed into concrete at the construction site and injected into inflatable forms which mold it into the desired shape. This will be done using a robotic astronaut or "Astrobot" which is currently under development by Kader Robotics. The Astrobot would be used to operate the inflatable concrete form and connect the concrete modules. It would also install supporting equipment before human habitation.

The inflatable forms would consist of three primary components (outer netting, outer membrane and inner membrane). The outer netting would provide the tensile reinforcing for the structure as well as give it shape. The outer membrane provides the outer surface for the form. The inner membrane has several functions. First, it is the inner surface of the form during curing. Secondly, the membrane contains the gas used for inflating the system. It would also serve as a seal for a pressurized structure as would be required for human occupancy. Interfaces with accessory systems such as air locks, antenna, or additional modules could be previously installed in the form. Holes for windows, conduits, hatches, etc. could also be prefabricated in the form or cut into the set concrete structure.

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## Applying the Orbit Transfer Vehicle to Lunar Logistics

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The Orbit Transfer Vehicle (OTV), representing the next generation of high performance upper stages, is currently under study in a Phase A contract managed by NASA's Marshall Space Flight Center. This work has concentrated on near-Earth applications as well as delivery to lunar orbit. In the past year, the feasibility of using an OTV for lunar surface logistics has also been investigated. This application requires the adaptation of a previously orbit-only vehicle to the touchdown and lunar surface environment. Several issues had to be considered for the development of vehicle concepts as will be discussed in this paper.

Mission payload masses set the vehicle size and are derived from NASA/JSC lunar studies. These include delivery of 40000 lb. modules to lunar orbit and the lunar surface as well as a round-trip 15000 lb. manned craft. These payload sizes result in  $\text{LO}_2/\text{LH}_2$  propellant capacities on the order of 100,000 lb. The mission design is critical to the overall performance of the vehicle. Several options were considered including direct transfer (Surveyor type) as well as the use of lunar orbit and the  $L_1$  libration point as hardware transfer locations. Mission analysis made use of a three-body integrated simulation having propulsive  $\Delta V$  capability. These mission options were combined with various vehicle staging scenarios to derive the most efficient transfer technique.

Vehicle configuration issues were considered to assess the feasibility of modifying an orbital vehicle to perform lunar landings. Subsystem impacts included core structure, propellant tank sizing, engine quantity / throttling requirements, landing legs, meteoroid shielding, radar, and aerobrake impacts. The core structure had to be able to withstand higher loads resulting from a more energetic aeroassist - this impact was kept relatively small through the use of load relief in the aerodynamic phase.

Significant changes occurred in the main propulsion module. Accomplishment of a soft landing introduces throttling requirements which when coupled with engine-out considerations drive the thrust range to 20:1. This requirement can be met by an advanced cryogenic engine. The requirement for vertical alignment during landing with a worst-case engine out results in a four engine cluster as the basic propulsion module. The landing leg design is driven by stability considerations as well as impact shock attenuation. A concept was produced which could be integrated into either an aerobrake (round-trip vehicle) or into the stage core alone (dedicated lander).

Return aerobraking in the Earth's atmosphere presents significant problems due to the higher energies which must be dissipated over those encountered during return from geosynchronous orbit. To maximize OTV commonality and performance, it is desirable to minimize core structural modifications as well as aerobrake size growth. The most significant problem is with peak g-loads which are controlled by slightly oversizing the aero control corridor and flying a entry profile that is biased high for load relief. This results in a slightly higher angle of attack of  $8.83^\circ$  as opposed to the  $7.23^\circ$  used in GEO-return applications.



**MODULAR EVOLUTIONARY SYSTEM ARCHITECTURES FOR MANNED  
EXPLORATION**

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Goals for human exploration and development of the Moon and Mars face a difficult affordability problem. The challenge to the engineering community is to find ways to achieve these goals at lower cost, thereby improving prospects for obtaining a national commitment to their accomplishment. This paper presents the beginnings of a systematic approach.

Lunar and Mars mission profiles and mission requirements are summarized to define the ranges of requirements that must be satisfied by system designs for manned missions, from exploratory sorties through permanent installations. While lunar mission profiles are reasonably consistent over time, Mars mission profiles vary widely from one opportunity to the next. The paper gives particular attention to the Mars opportunity variability problem (including opposition, conjunction, and Venus swingby options) and how it can be dealt with in systems design so as to avoid a unique design solution for each opportunity. It is shown that vehicle sizing and configuration arrangements can be made similar for lunar and Mars applications.

A concept for modular systems architecture is presented. This concept achieves commonality between lunar and Mars vehicle systems and provides evolutionary paths that minimize the cost of a program of exploration and development.

Program strategies for affordability, including initial costs, life cycle costs, and annual funding, are presented and discussed.



LUNAR ECOSYSTEM AND ARCHITECTURAL PROTOTYPE (PROJECT LEAP), S.W. Ximenes, F.J. Winisdoerffer, J.D. Brown, Sasakawa International Center for Space Architecture, University of Houston

The University of Houston's Sasakawa International Center for Space Architecture is pursuing research and design studies for permanent lunar settlements. One such study, Project LEAP (which stands for Lunar Ecosystem and Architectural Prototype) has produced staged growth concepts for a habitat to support lunar mining operations. The project has been undertaken in cooperation with the Advanced Programs Office and the Solar System Exploration Division at the NASA-Johnson Space Center.

The principal purpose assumed for the development is to produce liquid oxygen and hydrogen propellant for an Advanced Space Transportation System and future orbital infrastructure consumption. The base has been designed to grow over a ten year period from an initial six-person crew occupancy to an advanced facility capable of accommodating as many as one hundred and fifty people. Evolutionary growth stages would rely increasingly upon acquisition, processing and utilization of lunar materials to optimize self-sufficiency. Achieving large volumes of habitable space within a relatively short period of time, and with minimum requirements for construction processes is a major objective in the overall growth plan of the core facility. This is accomplished in part by a planned deployment of three basic module components which determine the eventual layout of the facility. These three components, the common module, the interconnect node, and the airlock are delivered to the lunar surface according to a growth scenario dictated by increased personnel needs and operational readiness of base functions. Due to the hexagonal design of the interconnect node a "circle the wagons" approach allows the common modules to form perimeters of floor space which can then be enclosed with inflatable domes. The resulting geometry develops a honeycomb pattern of volumetric growth that evolves in stages to produce dedicated areas for habitation, laboratories, and farming/life-support functions.

Project LEAP's study objectives have sought to identify incremental site development and facility requirements; identify candidate site development and construction options; propose site layout and habitat design/growth concepts; and survey requirements to achieve a high level of self-sufficiency. As an ongoing research and development program, the project has evolved from research and data collection for concept and design to the production of 3-d solids computer modeling. A 1/30th scale architectural model of a representative lunar base site has been constructed depicting facilities for habitation, mining, transportation, power, communications, refining, and storage.

## SYNERGISMS BETWEEN THE MARS AND LUNAR PROGRAMS

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As America prepares for the next century of space exploration there are two bodies that are viable candidates for manned bases - the Moon and Mars. Both of these bodies have advantages and disadvantages when being considered for manned bases. The Moon has advantages in that it is an easily reached body with frequent favorable launch opportunities where human adaptability and equipment reliability can be safely tested. The primary disadvantage of the Moon is that it lacks abundant critical natural resources such as hydrogen and water. On the other hand, Mars has the advantage of an abundance of natural resources, two moons that might be composed of 20-40 per cent water and a much more geologically interesting environment. The primary disadvantage of Mars is the travel time and the fact that favorable launch windows occur approximately every 2 years.

As part of a Manned Mars Mission study for Marshall Space Flight Center an investigation into using other areas besides Low Earth Orbit for low and high thrust missions to Mars has been conducted. This paper will deal with a Mars mission utilizing a lunar orbit for departure and return and the possible synergistic interactions between the Lunar and Martian programs. Particular emphasis will be placed on using the Moon as a testing ground for equipment and crews for the Mars mission and the return of water and other volatiles from Mars for use at the lunar base.