Thoughts on a Lunar Base

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I would like to start with a statement that I expect and even hope, may be controversial. I believe there is a very great difference between the space station now being planned and any activity on the Moon now under discussion. I believe that in the space station we should do as much as possible with robots for two simple reasons There is nothing in space—practically nothing—except what we put there. Therefore, we can foresee the conditions under which we are going to work and, in general, I think robots are less trouble than people.

The other reason is that apart from experiments and special missions that we have in space, we do not want to proceed to change anything in space, whereas on the Moon we will want to change things Likewise on the Moon, we will find many things that we do not expect Adapting robots to all the various tasks that may come up, and that we do not even foresee, is not possible.

The space station is obviously extremely interesting for many reasons However, that is not what I want to talk about except to state that of course the space station is apt to develop into a transfer station to the Moon. Therefore, its establishment is not independent of what we are discussing here.

I would like to look forward to an early lunar colony. I do not want to spend time in making estimates but simply want to say that it would be nice to have a dozen people on the Moon as soon as possible. I think we could have it in ten years or so. When I say 12 people, I do not mean 12 people to stay there but to have 12 people at all times, to serve as long as it seems reasonable. To me, 3 months is the kind of period from which you could expect a good payoff for having made the trip. Longer rotations than that might be a little hard, and efficiency might come down. But all this is, of course, a wild estimate on my part

What kind of people should be there? It will be necessary to have all of them highly capable in a technical manner, and I believe that they should perform all kinds of work. Probably at least half of them, after coming back to Earth, should get the Nobel Prize. The result will be that we will soon run out of Nobel Prizes because I believe there will be very considerable discoveries

Also, if you have 12 people you probably ought to have a Governor. I have already picked out the Governor to be, of course, Jack Schmitt Furthermore, I would like to tell you arrangements you can approach temperatures in the neighborhood of 2.7 degrees Absolute. In this way you can get low temperature regions of large volume and high temperature regions of large volume.

Now, I would like to talk about one practical point that may not have been discussed, namely, the question of where on the Moon the colony should be I would like to go to one of the poles because I would like to have the choice between sunlight and shade with little movement Furthermore, it would be a real advantage to establish the colony in and around a crater where you might have even permanent shade in some places and where moving away from the rim on one side or the other you can vary conditions quite fast Of course, it is of importance not only to position yourself in regard to the Sun but also in regard to the Earth. For many purposes you want to see the Earth in order to observe it For other purposes for instance astronomy, you want to be shielded from the Earth, not to be disturbed by all the terrestrial radio emission. All these conditions will be best satisfied in a crater near a pole

I have a little difficulty in reading the lunar maps There seem to be three good craters in the immediate vicinity of the south pole but no good craters near the north pole, or vice versa I am not quite sure. At any rate I want to go to the pole that has the craters

The purpose of all this is obviously what I have said to begin with and what you all realize—refueling and energy. Oxygen is the main point but it would be nice also to have hydrogen. Hydrogen we could get from the Earth much more cheaply than the oxygen, but still it is one-ninth the cost of oxygen plus the considerable weight of the tank Hydrogen has been deposited in the lunar dust by the solar wind over geologic time, and the mass of hydrogen in that lunar dust as far as I know, is not much less than one part in ten thousand. Without having made a decent analysis my hunch is that it is easier to move the lunar dust a few miles on the Moon than to come all the way from the Earth even though you have to move ten thousand times the mass If you can distill oxygen out of iron oxide, you certainty can distill hydrogen out of the lunar dust Furthermore, Jack Schmitt tells me that there is a possibility offending hydrogen, perhaps even hydrogen that is four and one-half billion years old, in other parts of the Moon in greater abundance than what we see in the average lunar dust

All of this is, of course, of great importance and perhaps serves as a little illustration of what kind of constructions we are discussing. Obviously, we will have to try to make these constructions with tools as light as can be transported from the Earth. In planning the lunar colony, special tools and special apparatus have to be fabricated on the Earth, specgicalty adapted to the tasks already described as well as others.

I would like to make a special proposal. I believe that surveillance of the Earth—permanent continuous surveillance that is hard to interfere with—is an extremely important question, important to us, important for the international community, important for peace keeping. There have been proposals, and I am for them, to guarantee present observation offacilities by treaties. On the other hand, treaties not only can be broken; treaties have been broken. It is in everyone's best interest to have observation stations that are not easy to interfere with.

I would like to take the biggest chunks that I could get off the Moon and put them into a lunar orbit, perhaps 120 and 240 degrees away from the Moon. Of course they will be very small compared to the Moon but maybe quite big compared to other objects that we put into space. If the Moon and these two additional satellites are available for observation, then we can have a continuous watch on all of the Earth with somewhat lesser information around the pole. The latter also can be obtained with additional expenditure, but to have 95 percent of the most interesting part of the Earth covered continuously would be already a great advantage. I would be very happy if, on these observation stations, we would do what we should have done with our satellites and are still not doing namely, make the information of just the photographs obtained from the satellites universally available. I believe that would be a great step forward in international cooperation, international relations, and peace keeping

Traveling to these artificial satellites from the Moon is a much smaller job than reaching them from the Earth. Since you stay on the same orbit you just have to have a very small additional velocity after leaving the Moon, wait until you are in the right position, and then use a retrorocket The total energy for that is small, and ifyou produce the rocket fuel on the Moon, then I think you have optimal conditions

I also would like to have a satellite with a special property. It should have as big a mass as possible built up from a small mass in the course of time. But furthermore I want it to rotate in such a manner that instead of turning the same face all the time to the Earth it should turn the same face all the time to the Sun. If you can do that then half of the surface will be in permanent night half in permanent illumination, and whatever we can do on the Moon, for instance setting up a permanent low-temperature establishment, you can do that very much better on these satellites

Now, I would like to finish up by making a very few remarks on purely scientific work that will become possible. In the vacuum of the Moon we can work with clean surfaces. It is obvious that surface chemistry could make big strides This can be done equally well in the space station, and, in this respect the Moon does not have an obvious advantage.

Where you do get an obvious advantage is in astronomical observations where you want the possibility to collimate in a really effective manner. When you want to look at x-rays or gamma rays from certain directions all you need to do is to drill a deep hole that acts as a collimator and have the detectors at its bottom. You would have to have a considerable number of these holes, but I believe that it will be much cheaper than to have a considerable number of observation apparatus shot out from the Earth, particularly because the mass for collimation will be not available in space stations except at a considerable cost The same holes may be used for high energy cosmic rays

Another obvious application is in high energy physics As the size of accelerators kept going up, many years ago our very good friend Enrico Fermi at a Physical Society meeting as far as I know, made the proposal in completely serious Italian style that sooner or later we will make an accelerator around the equator of the Earth. Well, we are approaching that—at least we are planning an accelerator that takes in a good part of Texas I am not quite sure that we should do that Let us wait until we get to the Moon. (That might happen almost as soon as a giant accelerator can be constructed.) We actually could have an accelerator around the equator of the Moon. Taking advantage of the vacuum available, you only need the deflecting magnets and the accelerating stations and these can be put point for point rather than continuously.

I have been interested for many years in the remarkable discovery of Klebesadel at Los Alamos of gamma ray bursts that last for longer than 15 milliseconds and less than 100 seconds have their main energy emission between 100 and 200 kilovolts but seem to have components far above a million volts too. I believe everybody is in agreement that these come from something hitting neutron stars and converting the energy into gamma rays But most people believe that they come from nearby regions of our galaxy and are, therefore, isotropic. Actually the number of observations depends on the intensity in such way as though from more distant places we do not get as many as expected. The usual explanation is that we get these from farther places and we get them only from the galactic disc rather than a sphere. Unfortunately these bursts are so weak that the directional determinations cannot be made. On the Moon you could deploy acres of gamma ray detectors of various kinds and leave them exposed to the gamma rays or cover them up with one gram per square centimeter, five grams per square centimeter, or ten grams per square centimeter so that with some spectral discrimination you will get a greater intensity from perpendicular incidence than from oblique incidence. As this apparatus will look into the plane of the galaxy, into the main extension of the galaxy, or toward the galactic pole, you should see a difference, a deviation from spherical distribution, for these weakest bursts, essentially bursts of 10^(- to

A very good friend, Montgomery Johnson (who unfortunately died a few months ago) and I had made an assumption that these radiations really do not come from the galaxy but from outer space, from regions where the stars are dense and where collisions between neutron stars and dense stars like the white dwarfs may occur. Good candidates are the globular clusters but there may be other dense regions in the universe as well. If this hypothesis turns out to be correct then the reason you find fewer events at great distances are cosmological reasons—curvature of space. a greater red-shift lesser numbers of neutron stars and white dwarfs in the distant past which was closer to the beginning of the universe. Actually, if this hypothesis is correct, then the gamma-ray bursts would in the end give us information about early stages of the universe. No matter which way it goes the gamma-ray bursts are interesting phenomena, and the Moon is one of the places where they could be investigated with real success

I am sure that in these ways and many others an early lunar colony would be of great advantage.

LUNAR BASE DESIGN

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A successful lunar base operation must have appropriately designed structures to house and facilitate the performance of its functions and personnel and to respond to the very special problems of the irradiated, near vacuum lunar environment This paper on lunar base design proposes the concept of a radiation shield with pressurized enclosures underneath It examines a range of factors related to base planning, including shielding considerations. Several ways of designing and balding shields are described in detail, and the form and location of pressurized enclosures outlined. The paper also enumerates the related areas of needed research, development, and testing work upon which further progress will depend

INTRODUCTION

Various impressions of extensive future "lunar cities" and base complexes have recently been proposed and illustrated. By terrestrial standards, most anticipate a large building operation, considerable quantities and weights of building materials, fairly heavy plant and equipment, and a sizable labor force. In view of the high cost of transport and the unknown performance of building materials and structures in the irradiated vacuum lunar environment as well as other factors, a different strategy is proposed.

An approach for the post-camp phase base is advocated that proceeds from particulars to generalities. Starting from a small building of simple configuration, it expands to testing and evaluation of materials and structural concepts. With this experience the base grows in stages to a larger installation, becoming more self-sufficient and using more lunar resources. An incremental approach contrasts with some earlier proposals that show sizable and finite arrays of structures built in one operation. It is doubtful that a large base is initially required or could even be built, and its design would probably be out of date before completion.

It is important to take time now to plan a long-range physical development strategy for the lunar base. This will guide the design thinking and be reflected in the initial shape of the complex An evolutionary approach will probably generate a linear layout for the base, reflecting incremental growth, transportation, solar orientation, and excavation factors. The overall success of the lunar base operation will very much depend upon the building(s) and the structures) that will house a wide range of functions and processes.

LUNAR BASE CONCEPT

First generation structures of the post-camp stage would consist of two independent parts: pressurized enclosures under radiation shielding canopies. The size and shape of the enclosures will be determined by the dimensions of the operations they accommodate.

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As far as can be estimated, some large-span enclosures will be needed for the servicing and/or assembly of large pieces of equipment, including lunar surface and spacecraft, telescopes, etc. However, the major part of the base could probably be interconnected spaces of fairly small dimensions that would still be much larger than camp stage modules and more economic to erect and maintain Therefore, both large- and small-area units must be considered

Although the post-camp stage objective is ultimately to develop an entirely lunar-based construction capability, this would be difficult in the beginning. Structures for radiation shielding will use lunar regolith, but pressurization will generate tensile forces that cannot be handled by first generation regolith processing such as the fabrication of relatively simple ceramic/glass block components. Nevertheless, structures with floor areas larger than those provided inside imported camp stage modules must be erected as soon as possible.

At a later phase in the evolution of the lunar base, shielding and pressurization might be combined in structures entirely fabricated from regolith However, this would occur after the base has a fairly large combined floor area to house the necessary plant with workshop capability. A second generation building system combining pressurization with shielding using regolith in a rigid system, must be able to accommodate tensile stresses generated by pressurization and temperature movement. Speculation on second generation structures suggests a flat or almost flat upper surface to support regolith shielding. Curved forms can better handle pressurization, but loose regolith cannot be heaped onto the steeply inclined surfaces of some curved forms. Outer skirt walls under flat or arched shields must be able to accommodate tensile stresses resulting from the outward push of pressurization. The way this will be done depends upon the manner in which the regolith is used Skirt wall panels using interlocking ceramic components can be prestressed vertically; panels using cements or epoxies as bonding agents with regolith aggregates could also employ short filament glass fibres for reinforcement within the mix. Sealing between panels could be provided by adhesive tapes applied internally and kept in position by outward pressure.

As mentioned at the beginning of this paper, impressions of some lunar bases presented over the past few years suggest enormous technical problems. The designs and options presented by this author indeed reveal technical unknowns. However, the required information and solutions can be obtained through research and development, some main areas of which have been outlined These indicate that an integrated program of planning research, and design can lead to the building of a lunar base within an optimum time frame.

PRELIMINARY DESIGN OF A PERMANENTLY MANNED LUNAR SURFACE RESEARCH BASE

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

INTRODUCTION

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

TRANSPORTATION SYSTEM

Three major components of a transportation network were assumed to be in existence before the reconnaissance mission began These elements included the space shuttle, a low-Earth-orbit staging point (presumably the space station), and a high performance space-based OCV. Only the ON element required further definition for the purposes of this study. The OTV used here are configurations proposed by NASA/JSC (Lineberry, personal communication, 1983) for use in Earth-orbital applications and for high-energy interplanetary missions. Each OTV has a maximum 27,216 kg (60,0001b) of usable propellant and *an* L_4, *of* 460 *seconds* (LH2 LO_2). *A* thrust *level of* 147,000 N (33,000 lbf) *was assumed,* which is representative of two RL-10 engines. The gravity losses corresponding to the

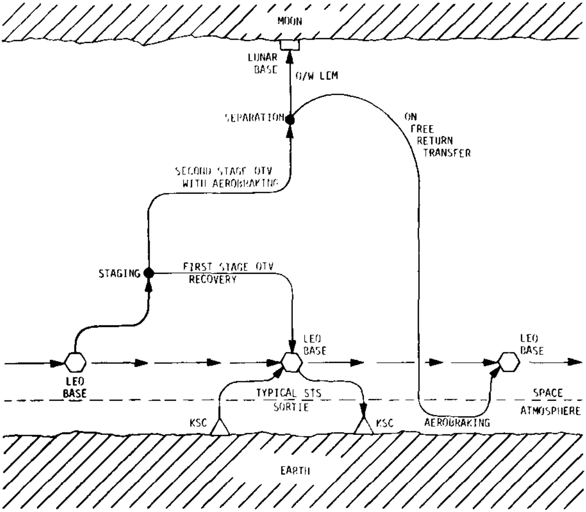

Figure I. One way, unmanned *cargo delivery* mode.

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

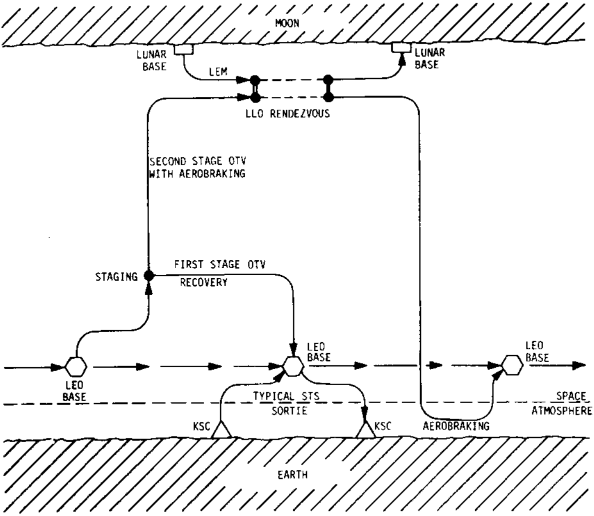

Figure 2. Manned sortie mode.

SITE RECONNAISSANCE AND SELECTION

An exploration team consisting of four individuals would spend up to 30 days exploring a region 50 km in radius that has been previously selected from remotely obtained data. TWo surface vehicles would be used with two crew members per vehicle to carry out the exploration (Science Applications International Corp., 1984a). For safety reasons these vehicles would operate in tandem rather than individually. The two surface exploration vehicles would each consist of a rover and a trailer, the latter containing crew quarters and experiment facilities. The rovers would have the capability to move moderate amounts of lunar soil in order to expose subsurface strata. With the exception of the science experiments, both rovers and trailers would be identical and capable of supporting the entire crew under emergency conditions. A mass budget of 2400 kg has been assumed for the instruments needed to ascertain which site Is best suited for the base. These instruments would focus on the local composition, seismic characteristics, and stratigraphic make-up of each candidate site. Preliminary data analysis would be conducted on board the two trailers with more detailed analyses to be carried out upon return to Earth. These analyses would support the final site selection for the permanent base.

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

OPERATIONAL BASE

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

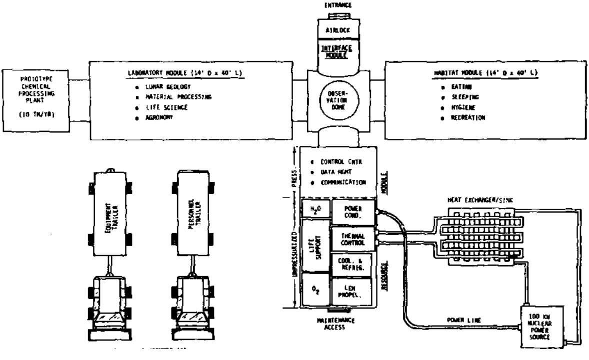

Figure 3. *Initial* base *concept* (7-person crew).

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

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

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

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

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

At completion of mission

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

SUMMARY

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

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

	Reconnaissance	Surface Base	Total
Surface modules			10.2
Shelter	0.1		
Trader (2)	1.5		
Rover (2)	1.4		
Permanent modules (4)		5.8	
Chemical processing plant		0.9	
Nuclear power plant		0.5	
Propulsion stages			164
Lunar excursion module	2.7	1.4	
Lunar logistics lander	2.7	3.6	
OTVs	0.8	3.0	
0T V crew module	1.6	0.6	
On-orbit assembly and test	1.0		1.0
STS			10.0
Reconnaissance (12 launches)	1.3		
Base deployment (25 launches)		2.7	
Base operations (18 launches per year)		6.0	
Operations			14.5
Mission control center	0.5	2.1	
'training/operations development/ management	2.0	5.0	
Mission (orbital and flight operations)	0.7	3.1	
Logistics	02	0.9	
Totals	16.5	35.6•	52.1

'Includes 3^y ops at surface base

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

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LAVA TUBES: POTENTIAL SHELTERS FOR HABITATS

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Natural caverns occur on the Moon in the form of "lava tubes," which are the drained conduits of underground lava rivers. The inside dimensions of these tubes measure tens to hundreds of meters, and their roofs are expected to be thicker than 10 meters. Consequently, lava tube interiors offer an environment that is naturally protected from the hazards of radiation and meteorite impact Further, constant, relatively benign temperatures of -20°C prevail These are extremely favorable environmental conditions for human activities and industrial operations. Significant operational, technological, and economical benefits might result if a lunar base were constructed inside a lava tube.

INTRODUCTION

This paper addresses the existence of natural caverns on the Moon in the form of "lava tubes," and it suggests that they could provide long-term shelter for human habitats and industrial operations.

The origin of lava tubes is genetically related to the formation of "sinuous rilles," which represent flow channels of molten lava Such channels generally form at high extrusion rates of low viscosity magmas. Sinuous rilles are abundantly observed on lunar basalt surfaces (eg., Oberbeck *et al.,* 1969, 1971; Greeley 1971, 1972; Cruikshank and Wood, 1972; Head, 1976). The distribution of sinuous riles on the lunar front side was mapped by Guest and Murray (1976).

Lava tubes are well known from basaltic volcanic terranes on Earth (Ollier and Brown, 1975; Greeley, 1971, 1972, 1975; Cruikshank and Wood, 1972; Hulme, 1973; Peterson and Swanson, 1974). A number of processes may contribute to their formation (l) radiative cooling may cause surface crystallization and crusting-over of the liquid lava. (2) Commonly, such relatively thin crusts break apart and collapse because the melt below continues to flow. Solid but relatively hot chunks of this crust will raft on the lava river and may coalesce into larger and larger aggregates until a solid roof forms. (3) Radiative cooling takes place at the sides of such lava flows, leading to crusting and aggregation of solids and ultimately to the buildup of pronounced levees, which in turn increase channelled melt flow. Additional aggregation from these levees, aided by spattering of lava splashes, can lead to the formation of solid roofs.

Commonly, low viscosity magmas are also very hot Hulme (1973) and Peterson and Swanson (1974) present field observations that lava tube cross sections may be modified and enlarged by thermal erosion, i.e, by remelting of the tube's ceiling, walls, and floor.

Typical heights and widths of terrestrial lava tubes are generally measured in a few meters; cross-sectional dimensions in excess of 10 m are rare. The length of lava tubes on Earth may reach 10 to 20 km, but most tava tubes are only 1-2 km long. Greeley (1975) points out that the frequency of such underground lava conduits on Earth may have been underestimated in the past and that they are indeed relatively common around terrestrial shield volcanoes such as those in Hawaii.

LUNAR LAVA TUBES

High extrusion rates and extremely low viscosities characterize lunar basaltic volcanism (Moore and Schaber, 1975), conditions very conducive to the formation of lava channels and tubes. Open channels in the form of sinuous rilles are very abundant on lunar basalt surfaces. Their widths and depths are typically hundreds of meters, and they are commonly a few tens of kilometers long. They are, thus, much larger than their terrestrial analogs (e.g., Oberbeck et al., 1969, 1971). Indeed many of the above studies address the problem of how to properly scale the dimensions of terrestrial lava channels and tubes to their much larger counterparts on the Moon Hulme (1973) argues for increased turbulence and increased thermal erosion during lunar basalt flow. In detail, the highly meandering nature of many lunar rilles is also not observed to the same degree in terrestrial analogs. Increased meandering is probably best explained by reduced gravity and extremely shallow flow gradients.

In contrast to numerous open flow channels in the form of sinuous rilles , bona fide lava tubes are rarely observed on the Moon; they could indeed be rare geologic features. On the other hand, they are subsurface and will therefore generally not show up in lunar surface imagery. The only lava tubes that can be recognized from lunar surface photos are those that have partially collapsed roofs. Thus, little can be surmised about the absolute frequency and global distribution of lunar lava tubes. They may well be more common than can be demonstrated at present The important point and the crux of this paper is, however, that they do exist on the Moon

Figure 1 shows a lava tube with large segments of collapsed roof. A modest topographic ridge forms the crest of the tube as pointed out by Oberbeck *et al* (1969). The elongated depressions must be caved-in portions of this ridge system. Their elongated plane view and the lack of any raised rims distinguishes these depressions from circular impact craters. Note also the highly braided nature of the elongated depressions, in stark contrast to the random distribution of circular impact features dotting the surroundings. This observation in particular lends additional credence to the interpretation that the entire linear feature is a partially collapsed lava tube. Figure 2 represents another feature interpreted by Cruikshank and Wood (1972) as a partially collapsed lava tube. This tube seems to be unusually straight The width of the open rille is approximately 200 m, and the uncollapsed roof segments are a few hundred meters long. Note the size of impact craters that were suffered by the seemingly intact roof segments.

What do we know about the roof thicknesses of lunar lava tubes, and are these roofs sufficiently massive and structurally stable to provide long-term shelter against measured as accumulated dosage over a period of time. This will consist of high intensity, unshielded lunar surface exposure together with some very low intensity radiation under the shield To maximize the permissible time that a person can work unprotected on the lunar surface, or indeed at the lunar base itself, radiation dosage, when not actually engaged on surface operations, must be minimized.

This will affect the design of the base in two ways. First, all parts of the base should be consolidated under one shield as far as is practical In this way, no unnecessary radiation dosage will be accumulated by personnel in moving between different installations and parts of the base, as would be the case with a fragmented based layout. Second, the effectiveness of the shielding should be maximized Some parts of the base must be separated from the main installation for operational and safety reasons; connecting links must be shielded in those cases. Since the radiation flux is isotropic, the edges of the shield must also be protected by regolith mass to screen out horizontal infiltration. Entrances should be labyrinthine, with overlapping screen walls to effectively block radiation.

Several options are viable for the design of the shield support structure and are described as follows. The first bays of the support structure would need to be erected quickly to give a radiation-free work area; therefore, they would probably utilize entirely terrestrially manufactured components

BASE STRUCTURES

Flat Shield, Pressurized Enclosures Beneath (Figs. 1,2)

The structure supporting the regolith consists of floors resting on deep lattice girders connected to columns and erected in sections. The bay dimension of the structure and

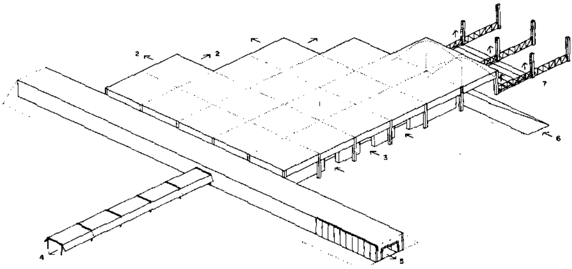

Figure 1. BASE CONCEPT I. Flat shield raised in sections, pressurized enclosures beneath. Overall view of base. (1) Regolith shielding (2) Perimeter expansion (3) Base entry through overlapping radiation border wall; from lunar surface equipment and installations 'park' (4) Solar shaded links to other parts of base. (5) Shielded links to other parts of base. (6) Ramp access to lower levels (7) Initial erection sequence.

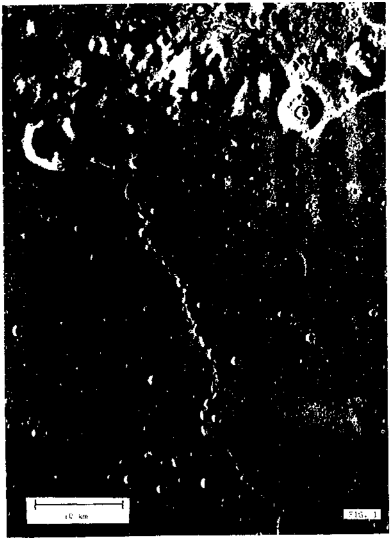

FIG. 1

Figure 1. One of the most prominent lunar lava tubes, first described in detail by Oberbeck et al. (1969). The lava tube is approximately 40 km long and up to 500 m wide. Note that some sections of the roof are uncollapsed and that the tube continues underground toward the south (at bottom of picture). Also, note that slopes leading into the rille may be of different steepness' the flatter. ones might be negotiated with ease Uncollapsed sections of the tube are on the order of a few hundred meters long particularly in the northern part Dimensionally, these lava tubes would be more than adequate to serve modular habitats and a variety of machinery. Note that this lava tube happens to be within a few kilometers of a highland contact and it is not inconceivable that access to different raw materials may be possible from a single lava tube /Lunar Orbiter 5, frame 182. Northern Oceanus Procellarum).

radiation and meteoroid bombardment? According to Oberbeck *et al.* (1969), the ratio of roof thickness (TO of terrestrial lava tubes relative to typical dimensions of tube cross sections (Tc) ranges from 0.25 to 0.125. Oberbeck *et at.* (1969) also use simple structural beam modeling to calculate that basalt "bridges" spanning a few hundred meters are possible on the Moon provided they are at least 40-60 m thick. These estimates happen to agree with the terrestrial T_r/T_c ratios. Importantly, these estimates are also in good agreement with the following observations: uncollapsed roofs of lava tubes display impact craters a few tens of meters across (see Fig. 2), occasionally as large as 100 m. The diameter/depth ratio of small lunar craters is approximately 4 to 5 (Pike, 1977). Thus, crater excavation depths approaching 20 m can be demonstrated. Using ballistic penetration mechanics (e.g., Gehrlng, 1970) and associated spallation processes at the rear surface (the roofs ceiling) of a slab-like impact target, one can estimate conservatively that the

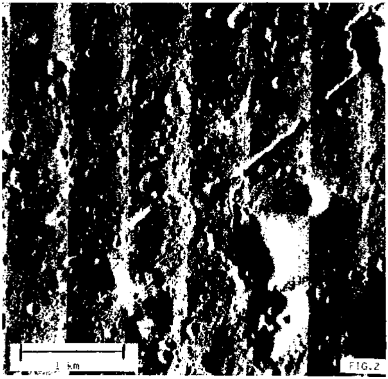

Figure 2. *Lunar lava rifle with* uncollapsed *roof* sections that *measure* hundreds *of meters* Note that *mountains are ciose* by *which* certainty *differ in* chemistry and *mineralogy from the* relatively *flat* basalt *surfaces.* This *Title* was *extensively* described by *Cruikshank and Wood (1972) (Lunar Orbiter 5, frame M-191i*

roof thickness must be at least two times larger than any crater depth; otherwise complete penetration of the slab (root) would have occurred. Following these arguments, the maximum crater sustained by an uncollapsed roof yields a minimum measure of roof thickness. The thicknesses of some lunar lava tube roofs are thus a few tens of meters. In principle, the minimum roof thickness of specific lava tubes could be assessed using the above crater-geometry relationships.

While impact craters indicate that initial roof thickness must have been substantial, the cratering process has also contributed to the erosion and structural weakening of such natural basalt bridges. Judging from the thickness of lunar soils on representative basalt surfaces, the uppermost 5-10 m of solid bedrock (lava tube roofs) are totally comminuted into fine-grained lunar soil. Penetrative cracks associated with this average regolith depth are a factor of 3-5 deeper on the basis of seismically disturbed areas below terrestrial craters (Pohl *et al.,* 1977). Importantly, the above-mentioned spallation process occurs at the tube's ceiling even for impact events that are not penetrative; i.e., it occurs as long as the stress amplitude of an impact-triggered shock wave exceeds the basalt's tensile strength (e.g., Horz and Schaal, 1981). This spallation-induced thinning and weakening is of more concern for the structural integrity of a given roof than surficial erosion. A few relatively large craters (>50 m) may have done more structural damage than the cumulative effects of many <20-m-diameter craters. Because meteorite impact is a stochastic process, it is difficult to predict the structural integrity and exact thickness of a lava tube roof with great precision. Nevertheless, rough estimates can be made via photogeologic techniques related to crater geometry as outlined above. An obvious strategy would be to select roofs or roof segments that have suffered relatively small cratering events only. Such segments are clearly safer than areas close to, if not directly below, a relatively large impact crater.

What do we know about cross-sectional dimensions of lunar lava tubes, and how do their interiors look? As indicated above, the linear dimensions of sinuous rilles and lava tubes are significantly larger on the Moon than on Earth; collapsed portions of some lunar lava tubes indicate correspondingly large tube interiors (see Figs. I, 2). There is little doubt that lunar lava tubes have large enough cross sections to house most any habitat. Restrictions and enlargements of cross sections occur in terrestrial lava tubes, but on relatively modest scales. The surface relief of terrestrial lava tube interiors can be highly variable, ranging from relatively smooth to very rough and knobby. However, this variability occurs on relief scales that are extremely small compared to cross-sectional dimensions. We can only assume that lunar lava tubes display similar relief In addition, the above-mentioned spallation products will have accumulated on the floor; they may possibly make initial trafficability cumbersome until removed or leveled (using readily available lunar soil as fill).

LUNAR BASE INSIDE A LAVA TUBE

Based on the foregoing, it appears that natural caverns of suitable sizes to house an entire lunar base exist on the Moon. Roof thicknesses in excess of 10 m will provide safe and long-term shelter against radiation and meteorite collisions. Creation of similarly shielded environments will constitute a significant and costly effort for any lunar base located at or close to the lunar surface. Substantial operational advantages for a lava tube scenario emerge as outlined below.

The primary suggestion advocated by this report is to use lava tubes merely as receptacles for prefabricated, modular habitats, either imported from Earth (initially?) or fabricated from lunar resources, if not in place (at later stages?). We do not suggest that the lava tube itself may be suitably modified to serve as the primary habitat There are too many uncertainties related to detailed geometry of the cross section and to the surface roughness of the walls and floors. Indeed, lava tube interiors may be too large, at least initially. Furthermore, penetrative cracks in the roof may exist, which would make it extremely difficult, if not impractical, to render the enclosed volume airtight. Modest site preparation inside the lava tube would consist of leveling the floor with lunar soil, an earth-moving operation similar in scale to site preparation on the surface. The lava tube would then be ready to act as a receptacle for self-enclosed habitats as well as for a large number of industrial operations, all safely protected from radiation and meteorite impact.

The primary advantage of housing the lunar base in a naturally sheltered environment is the potential to use extremely lightweight construction materials. None of the components would have to support any shielding mass whatsoever. Indeed, many components, such as a habitat shell, would not even have to support much of their own weight because they could be supported from the walls and ceilings of the lava tube. Habitats could even be inflatable, supported by air pressure only. In any case, construction and selection of materials would be entirely dictated by expected wear and tear. Widespread use of thin foil materials (metals, plastics?) is possible not only for the habitat itself, but also for a variety of ducts, storage tanks, *etc.* Any lunar base will include a variety of machinery located outside the man-rated, shirt-sleeve environment. Some of this gear will have to be protected against meteorite impact (e.g, all life-support systems). Much of this equipment will also have to be visited occasionally by crews for monitoring, maintenance, and repair. Inside a lava tube, the layout of this equipment could resemble that of terrestrial operations with all components freely exposed and easily accessed for inspection and repair. This seems particularly convenient for a variety of duct work, pipes, valves, storage tanks, etc., used to transfer gases and liquids. It is also possible to house some machinery inside lightweight shells to create an optimum environment for its operation (e.g., bio-processing plant). Such lightweight shells and habitats are easily connected with each other, providing great flexibility for expansion of the lunar base as well as for specific environmental engineering inside individual enclosures and compartments. In summary, numerous structural and operational advantages would present themselves if a lunar base could be designed and constructed without continuous concern for the hazards of radiation and meteorite impact.

Lava tube interiors offer additional environmental differences compared to the lunar surface. These differences may be beneficial for a number of engineering tasks and operational aspects. Being underground and some tens of meters removed from the lunar surface, there is a relatively constant-temperature environment (estimated at -20°C; Mendell, personal communication, 1985). This contrasts with the diurnal temperature cycle of -180° to +100°C at the surface. Temperature management inside a lava tube appears significantly easier than at the surface, where complex thermal insulation and control systems appear unavoidable. Also, the selection of materials functioning properly over a wide range of temperatures is severely limited at the surface; in contrast, a wide range of common materials maybe used at the more benign and constant temperatures prevailing inside a lava tube. Furthermore, inside a lava tube, all equipment is well shielded from IR and UV radiation. Materials (e.g., certain plastics) that otherwise deteriorate if exposed to this radiation could be used indiscriminately inside a lava tube. In short, additional environmental differences of a subsurface location may allow widespread use of common materials that may not be suitable for use on the lunar surface.

Some additional advantages for siting a lunar base inside a lava tube come to mind. The front and rear entrances of the tube may be sealed off rather readily to keep a relatively dust-free environment for all operations; loose dust may be a nuisance for a fair number of operations on the surface. It is also possible to conceive of lightweight, highly fexible suits for crews venturing outside the man-rated habitats but remaining inside the tube; neither thermal insulation nor meteorite impact is of great concern for such suits. Heavy, vibrating machinery may be solidly anchored to firm bedrock (a rarity on the lunar surface). The lava tube may serve as convenient "hangar" or "garage" for all kinds of equipment that have low duty cycles and that must be kept in a protected environment

A major operational drawback in utilizing lava tubes may be their difficult accessibility. Negotiation of perhaps steep slopes and the climbing in and out of a local "hole" appears cumbersome, possibly impractical. Relatively shallow sinuous rilles, somewhat flattened by impact craters, exist however. Also, the Apollo 15 crew visited the edge of Hadley rilles and felt that their Lunar Rover could have negotiated the slopes of this rille (Irwin, personal communication, 1985).

Location of a lunar base at the bottom of a hole seems not very economical from an energy point of view, because mass will have to be lowered and especially raised when needed on the lunar surface and when being readied for export to LEO or GEO. These energy considerations are, however, a matter of degree, because most large-scale industrial operations rely heavily on gravity for material transport Some modest elevation difference between the source of lunar raw materials and the processing plant is desirable even for such simple operations as sieving and magnetic separation For this reason, a lunar base may be more functional if located at the base of some slope. Why not a sinuous rille/lava tube where chutes or pipes may be laid out such that they terminate inside the lava tube at exactly that station where the high-graded raw materials are needed?

The most serious drawback in the utilization of lava tubes relates, however, to the present status of lunar surface exploration. Only a few lava tubes are recognized. High resolution photography of the entire lunar globe is needed to improve the inventory of lunar lava tubes and to determine their spatial distribution. Detailed imagery appears at present to be the only means for an improved understanding of their dimensions, roof thicknesses, and global distribution. Furthermore, lava tubes are viable candidates for shelters only if desired raw materials are close by. The distribution of specific lunar resources is also largely unknown at present It appears prudent to further explore the lunar surface and its resources via remote sensing from polar orbit Lava tubes are viable candidates to house a lunar base if basaltic raw materials are desired Lava tubes are, however, not excluded if non-basaltic resources were the ultimate choice. As illustrated in Figs. I and 2, lava tubes occur within kilometers of non-mare terrains with lithologies that differ substantially from the surrounding basalts.

CONCLUSIONS

Establishment of a lunar base, its construction, its layout, its diverse functions, and its ultimate location will be the compromise result of numerous scientific, technical, and economic considerations. Some of these considerations may be incompatible with housing a lunar base inside a lava tube. The simple purpose of this contribution is to remind everybody that natural caverns exist on the Moon. They provide a natural environment that is protected from meteorite impact, shelters against radiation, and is at a constant, relatively benign temperature. Such a natural environment allows widespread use of lightweight construction materials, great flexibility in the choice of such materials, and it results in improved operational capabilities. If a lunar base were emplaced on the lunar surface, a qualitatively similar environment would have to be engineered with great complexity and cost.

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MECHANICAL PROPERTIES OF LUNAR MATERIALS UNDER ANHYDROUS, HARD VACUUM CONDITIONS: APPLICATIONS OF LUNAR GLASS STRUCTURAL COMPONENTS

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lunar materials and derivatives such as glass may possess very high tensile strengths compared to equivalent materials on Earth because of the absence of hydrolytic weakening processes on the Moon and in the hard vacuum of free space. Hydrolysis of Si-0 bonds at crack tips or dislocations reduces the strength of silicates by about an order of magnitude in Earth environments However, lunar materials are extremely anhydrous, and hydrolytic weakening will be suppressed in free space. Thus, the geomechanical properties of the Moon and engineering properties of lunar silicate materials in space environments will be very different than equivalent materials under Earth conditions, where the action of water cannot be conveniently avoided. Possible of lunar glass for structural metals in a variety of space engineering applications enhances the economic utilization of the Moon.

INTRODUCTION

The intent of this paper is to consider the effects of the environmental conditions of the Moon and free space on the mechanical properties of lunar rocks and materials derived from them. Mechanical properties of silicate materials are very different in the anhydrous, hard vacuum conditions of space compared to Earth due to the virtual absence of hydrolytic weakening processes there. The implications of this realization will be very important in the interpretation of geophysical measurements in investigating the structure of the Moon, in exploitation of lunar materials for construction of a lunar base, and in eventual space industrialization and habitation.

After documenting what is currently known about these environmental effects, I concentrate on the implications of "anhydrous strengthening' of an easily formed structural material derived from lunar regolith, namely, lunar glass. Although the importance of lunar-derived glass has been known for some time (Phinney et *al.,* 1977), the full implications of the potentially very great strength of lunar glass in the vacuum environment are not widely realized. In detailing some applications of lunar glass structural components, 1 support a philosophy that requires maximal utilization of common lunar materials with minimal processing before end use. It has become clear that large-scale exploitation of space is limited by the cost of Earth-lift of materials. Therefore, it is essential that every possible means be taken to utilize indigenous materials from the Moon and eventually, the asteroids. In doing so, we should not fight the in situ environmental conditions (eg., low gravity, vacuum), or try to wedge Earth-derived processes into conditions for which they are not adapted; rather, we should attempt to take advantage of that which is given in new ways. It is in this sense that lunar glass can play a central role in easing full-scale entry into the new frontier of space.

HYDROLYTIC WEAKENING PROCESSES IN SILICATES

It has been known for some time that the fracture strength of brittle amorphous and crystalline silicates is determined in Earth environments by the damage state of surfaces and, most especially, the corrosive action of water in extending microcracks (Charles, 1958; Scholz, 1972). For example, the moisture sensitivity of glass is well known. Merely touching freshly formed glass rods will drastically reduce their tensile strengths, and less than one percent of the theoretical tensile strength of glass is normally realized in industrial practice (LaCourse, 1972). Similarly, the plastic strengths of crystalline silicates (e.g., quartz and olivine) at elevated temperatures and pressures are strongly affected because trace amounts of water aid dislocation motion (Griggs,1967; Blacic, 1972). In both instances, the weakening mechanism is believed to involve the hydrolyzation of Si-O bonds (Griggs, 1967; Blacic and Christie, 1984; Charles, 1959; Michalske and Freiman, 1982). A schematic representation of one proposed mechanism is shown in Fig. 1 (Blacic and Christie, 1984). The great inherent strength of silicates is due to the strength of the network-forming silicon-oxygen bonds. However, it appears that the polar water molecule can easily hydrolyze these linking bridges by replacing the strong Si-O bond with a hydrogen-bonded bridge that is an order of magnitude weaker. This hydrolyzation can occur along dislocations, thereby increasing the mobility of dislocation kinks, or at highly stressed microcrack tips resulting in a lower applied stress to propagate the cracks. In both cases, the net result is a large weakening of the material when even very small amounts of water are present

Whatever its detailed nature, the hydrolytic weakening mechanism is demonstrably a thermally activated rate process. Thus, the time- and temperature-dependent mechanical properties of silicates (brittle and plastic creep, static fatigue, subcritical crack growth) are dominated by moisture effects (Charles, 1958; Scholz, 1972; Blacic and Christie, 1984). As might be expected, these hydrolytic weakening processes are an important factor in such diverse areas as solid earth mechanics, geotechnology (drilling and mining), materials science (glass and ceramic technology), communications (fiber optics), national defense (high energy laser optics), and others, since, on Earth, it is practically impossible to avoid the presence of some water in the fabrication or use of materials, be they natural or synthetic. However, the case may be much different on the Moon and in free space.

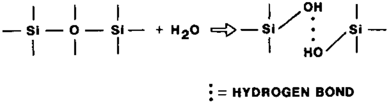


Figure 1. Schematic representation of the Si-O bond hydrolyzation reaction.

ANHYDROUS STRENGTHENING ON THE MOON

Although there is still hope that we may find some water preserved in the permanently shaded regions of the lunar poles (Arnold, 1979), a striking feature of all lunar materials examined so far is their almost total lack of water (Williams and Jadwick, 1980). The very small amount of water that is observed to evolve from heated lunar samples is likely due to either oxidation of solar wind-implanted hydrogen, present at about the 100 ppm level (Williams and Jadwick, 1980), or is the result of Earth contamination (Carrier *et al*., 1973). There is no unequivocal evidence of native water in any lunar sample returned to date. This fact suggests that, in the hard vacuum of space, silicates derived from the Moon will not, if we can avoid contaminating them, exhibit the water-induced weakening that is so ubiquitous on Earth. In other words, lunar silicates may possess very high strengths due to an "anhydrous strengthening" effect relative to our common experience on Earth. This possibility has numerous implications for space industrialization, some of which are explored below.

There is some supporting laboratory evidence for the anhydrous strengthening phenomenon in lunar or lunar-simulant materials. The compressive strength of a mare-like simulant rock (basaltic intrusive) has been shown to increase by about a factor of two when samples are degassed and tested in a moderate laboratory vacuum compared to tests in 100% humid air (Mizutani et *al.,* 1977). Subcritical crack velocity measurements in a lunar analogue glass demonstrate many orders of magnitude reduction in crack velocity with decreasing partial pressure of water (Soga *et al.,* 1979). This suggests that static fatigue processes will be strongly suppressed or absent in lunar materials in a vacuum environment. Several investigators have found that very small amounts of water strongly affect the dissipation of vibratory energy (Q^{-1}) in lunar and terrestrial rocks (Pandit and Tozer, 1970; Tittmann *et al,* 1980). These attenuation mechanisms are likely the result of the hydrolysis of crack surfaces with consequent reduction of surface energy in a manner similar to that shown in Fig. I. The soil mechanics properties of Apollo samples and simulants have been shown to be strongly affected by atmospheric moisture contaminants in moderate and ultra high vacuum experiments (Carrier et al., 1973; Johnson *et* at, 1973). These latter results suggest that well-consolidated lunar regolith may be substantially stronger than similar materials on Earth with important implications for energy requirements for handling of lunar materials.

There are many additional examples, too numerous to document here, of research on the effects of water on the mechanical properties of terrestrial silicate materials. The main conclusion to be gained from all this work is that water, even in trace amounts, is all-important in explaining the great reduction in strength of silicates. However, in order to get a quantitative estimate of the possible increase in strength of lunar materials relative to their Earth Counterparts, it is instructive to examine in some detail the elegant results of E M. Ernsberger (1969) on glass.

In Ernsberger's experiments, etched glass rods are heated and deformed to produce entrapped bubbles in the form of oblate spheroids. The bubbles concentrate stress at the point of maximum curvature of the bubble-glass interface in a calculable way. In

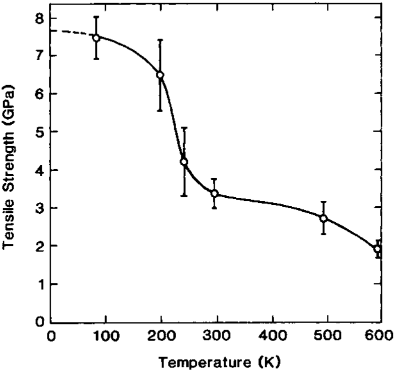


Figure 2. Tensile strength *of Kimble R6 soda-lime glass* in a *relatively anhydrous* environment *a function of temperature* (Ernsberger, 1969).

addition, if care is taken, failure always occurs at the flaw-free bubble surface where the atmosphere is constant and relatively anhydrous Using this technique, Ernsberger was the first to achieve controlled compressive failure of glass by shear fracture or densification. Scatter in tensile strength measurements was reduced compared to normal test methods; results are shown in Fig. 2 for soda-lime glass. The temperature dependence of strength shown in Fig. 2 is believed to be due to solid-state diffusion of weakening elements to the stress concentration, possibly sodium but more likely residual water dissolved in the glass. At reduced temperatures, the weakening element is immobilized and strength increases. The important aspect of this work, confirmed by other investigators for other glass compositions, is that the strength is about an order of magnitude higher ln an anhydrous environment than it is for the same glass tested in a normal humidity atmosphere. This gives some idea of what might be expected for a lunar glass used in vacuum, although it probably represents only a minimum strength estimate because of the extremely anhydrous nature of lunar materials and the hard vacuum of space.

SOME POSSIBLE APPLICATIONS

Table I compares the mechanical properties of some structural metals likely to be produced from lunar regolith with estimates for lunar glass. Common soda-lime glass under Earth conditions is also listed for comparison. The range of tensile strength estimated for lunar glass is believed to be conservative, as discussed above, but even if only the low end of the range can be achieved, then one can see that lunar glass is very competitive

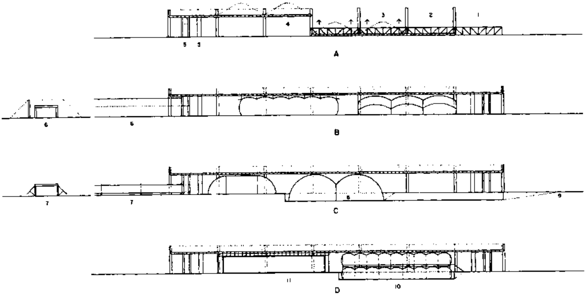


Figure 2. BASE CONCEPT I (see Fig I). *Section A showing erection sequence. (I)* Aluminum ***lattice girders and*** columns *in* ***place*** *(2)* Prestressed *floors* ***employing moulded regolith components attached*** *at ends* ***to girders*** *(3) Floor* loaded *with* regolith *raised* by *jacks* ***up column*** *guides* (4) ***Regolith leveled*** *off* Sections *B-D show range of*pressurized *enclosures shapes and types for different uses under shield. (5) Entry* through *overlapping radiation* barrier *walls (6)* Shielded *link to other part of base Bermed or with walled sides (7) Solar shaded link to* other *ports of base (5) Largo pressurized enclosures for big equipment maintenance. (9)* Ramp *access* to *lower levels (Lb)* Small *pressurized enclosures for* agriculture *etc (I I) Pressurized enclosure (to be deeloped later)* using impeivious membranes applied *to interior surface of* rectangular *enclosure.* Extra *top panels to resist outward* thrust *of pressure*

spacing of the *columns* will be influenced by the functions *of the* base and *the* pressurized envelopes underneath. *Column* spacing could be close *on one* axis, perpendicular to the floor span, and wide on the other, *or it* could be equally *spaced* on both *axes.* Flexibility in column spacing and relatively large *spans are* feasible. Because *of the 1/6 gravity* environment, the dead load *of dry* regolith *is not* high, and *the* lattice girders *can* be *very* deep *in* the thickness *of* the regolith.

The bays *of this* shield support structure would be raised by pneumatic *jacks to* the required *level, at which point* the *ends of the* beams would be permanently connected *to* the columns. The *regolith* overburden could be loaded either before erection *of* the structure or *after.* Placing regolith *at* ground level mainly involves pushing *operations, with some* leveling needed *after the* platforms *are* raised. Placing *regolith on* elevated floors requires lifting and reaching operations that requ*ire more energy* and equipment.

Prestressed floors. The floors would consist *of* moulded regolith components, prestressed from end to end *with* stranded fibre-glass *tendons* by *using* small, portable hand *jacks.* Components would *be* assembled flat *on a* leveled lunar *surface,* with *tendons* inserted *and* prestressed *to* form narrow *floor sections.* All sections would be connected *at* their ends *to* the transverse girders.

Table I. Mechanical Properties of Lunar-Derived Materials

	T (GPa/10^6psi)	p	E (GPa/10^6psi)	T/p (GPa/10^6psi)	E/p (GPa/10°psi)
Aluminum	0.17/0.02	2.7	70/10.2	0.06/0.009	25.9/3.76
Magnesium	0.20/0.03	1.7	45/6.5	0.12/0.017	26.5/3.84
Iron	0.28/0.04	7.9	196/28.4	0.04/0.006	24.8/3.60
Titanium	2.3/0.33	4.6	119/17.3	0.50/0.073	25.9/3.76
Alloy Steel	2.3/0.33	8.2	224/32	0.28/0.041	27.3/3.90
Soda-lime Glass (Earth Environment)	0.007/0.01	2.5	68/9.9	0.003/0.004	27.2/3.95
Lunar Glass (Space Environment)	0.007/0.01-3.0/0.44 or greater?	2.8	100/14.5?	0.003/0.004-1.07/0.16	35.7/5.19?

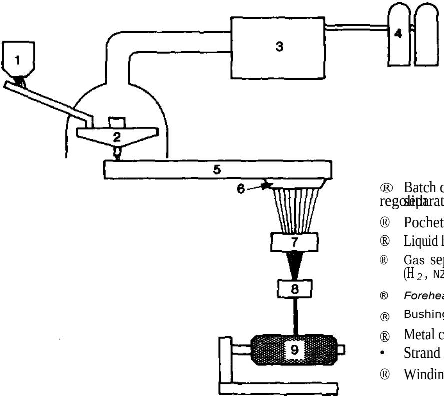
T = ultimate tensile strength
p = specific gravity
E = Young's modulus

with—if not superior to—the metals obtainable from lunar materials with considerably more processing effort.

How can lunar glass be utilized? One obvious way is in the form of glass fibers in tensile stress situations. Although lunar glass will be very strong, it will still be a very brittle material, and therefore it makes sense to distribute the load over many small elements whenever possible. Thus, lunar glass fiber cloths (Criswell, 1977) and multiply stranded cords and cables should see wide application in a lunar base and large space structures such as solar power satellites (SPS). However, lunar glass fibers should always be coated with a metal such as Fe, Al, or Mg to protect the glass from inadvertant or purposeful exposure to water vapor. Otherwise, a highly stressed glass component might fail catastrophically due to water-induced stress corrosion. The metal coating could easily be incorporated into the production process and would also serve the desirable purpose of protecting the fibers from mechanical damage during production handling or use. This is commonly done in terrestrial fiber glass production in the form of organic sizing coatings.

Figure 3 schematically shows the elements I believe will be required in a lunar or space-based glass fiber production plant I have assumed that sufficient electrical energy will be available [alternatively, direct solar melting could be used (Ho and Sobon, 1979)] and that there will be at least some minimal beneficiation of the feedstock No lunar or space-based processing plant should be without some means of capturing the rare but highly valuable volatile elements in the lunar regolith We also suggest in the figure that the relatively new Pochet-type furnace (Loewenstein, 1973) be investigated for use in lunar glass production because of the advantage it would seem to have in weight over traditional furnaces.

For applications requiring flexural, compressive, or mixed loadings such as for bulkheads in a habitat, or beams and columns in an SPS, fiber glass composites would be advantageous. Of the many types of composite materials seeing increasing terrestrial



® Batch charging: magnetically-separated lunar regolith

® Pochet-type furnace

® Liquid helium cryosorption pump

® Gas separation and storage (H_2, N_2, C, He. Ar. S)

® Forehearth

® Bushing: Fiber formation

® Metal coating evaporatox

- Strand formation

® Winding: Strand take-up

Figure 3. Elements of a lunar-base glass fiber and gas recovery plant.

usage, two would be especially attractive for space applications: metal matrix and ceramic matrix composites Gas-tight metal matrix composites such as graphite-aluminum are now widely used in aerospace applications. If we follow the philosophy of minimal processing of lunar materials before end use, then lunar glass fiber (LG)-Fe matrix composites should be developed since native iron will be available from regolith beneficiation for fiber coating in any case. The lunar vacuum would make the diffusion bonding and liquid metal infiltration techniques (Davis and Bradstreet, 1970) of composite production advantageous. This lunar glass-metal matrix composite should be very useful in lunar base habitat construction. If a lighter weight composite is wanted (for example, for SPS applications), then silica fiber-Mg composites could be produced when a more sophisticated lunar processing capability becomes available.

Ceramic matrix composites offer some special advantages in certain applications. Large space structures such as antennas and support structures of an SPS are sensitive to the potentially large thermal strains associated with periodic eclipses. Table 2 lists thermal expansion coefficients for some structural materials. Note that glass generally has lower thermal expansivity than common structural metals, and also that some compositions derivable from abundant lunar materials (e.g., titanium silicate glass) exhibit extremely low thermal expansion. If one were willing to import from Earth small amounts

Table 2. Thermal Expansion

	DeltaL/L X010^- 6 0 e)
Aluminum	24.0
Magnesium	25.0
Titanium	8.5
Iron	12.0
Steel	12.0
Invar	1.2
E-Glass	4.8
Corning #7971 Titanium Silicate Glass	0.03

of graphite fiber (which has a negative thermal expansivity), then composites having zero thermal expansion could be produced (Browning, 1982). Ceramic matrix composites exhibit one other desirable property. If the reinforcement fibers do not chemically bond to the ceramic matrix, but instead are held dominantly by frictional forces, then the composite exhibits an enhanced ductility and residual strength beyond the yield point to relatively large strains and is notch insensitive in a manner similar to metals (A. Evans, personal communication, 1984). Thus, I envision a composite in which Fe-coated LG fibers are imbedded in a lunar glass matrix. Such a material may have very desirable structural properties and may represent the best structural material that can be formed entirely from the most common lunar materials with the least amount of processing.

Finally, I would like to support the suggestion of Rowley and Neudecker (1984) that lunar habitats be formed by melting in-place, glass-lined tunnels using the "subterrene" (perhaps in the present context, as they rate, better termed "subselene") technology. If the glass-lined tunnels were sputter-coated with a metal to protect the glass from water vapor, and if the LG fiber composites were used for bulkheads, etc., then extensive lunar habitats with more than adequate radiation shielding from the largest solar flare storms could be produced from 100% lunar materials. No doubt engineers and architects will find many more uses than we have thought of for a lightweight structural material with several hundred thousand psi tensile strength

RESEARCH NEEDS

Most of what I have advocated concerning the possible high strength of lunar materials in hard vacuum environments has been based on research of terrestrial silicates under terrestrial or, at best, poorly simulated space conditions. Ultimately, our contentions must be proved at full-scale using actual lunar materials under in situ conditions. A lunar-based materials testing laboratory would seem necessary for this and should be an early,. high priority lunar base facility. Until reoccupation of the Moon, however, much can be learned, and perhaps our basic contentions can be proved by experiments using lunar simulants formed and tested under ultra high vacuum laboratory conditions on Earth. This approach would seem initially preferable to LEO shuttle experiments because of the relatively poor vacuum environment of the shuttle resulting from the normally low orbits achieved and, perhaps more importantly, outgassing of the vehicle itself. Perhaps the free flying or tethered experimental platforms proposed in conjunction with the space station will improve this situation and will be needed to evaluate the effects of extended exposure to radiation and micrometeoroid fluxes, but for now ultra high vacuum experiments in Earth laboratories appear most appropriate. Most urgently needed are basic mechanical properties such as tensile and compressive strengths, fracture toughness, and thermal properties. With these results in hand, investigation of potential composite materials can proceed followed by bench top and proto-type engineering of the manufacturing facilities that will be required. Also, research and evaluation of the "subselene" approach to lunar habitat formation should proceed because of the advantages it would seem to have over imported structures.

SUMMARY

Although the apparent absence of water on the lunar surface makes it difficult to do many of the things we would like on the Moon, in at least one respect it may be a blessing. It appears that the anhydrous, hard vacuum environment and the inherently dry nature of lunar regolith materials down to the ppb level make possible the use of lunar glass for structural applications that would be impossible on Earth. In view of the fact that the initial cost of large-scale industralization and scientific exploitation of the space environment is dominated by Earth-lift requirements, the possible extensive use of lunar glass structural materials in a wide variety of applications offers promise of very large savings in Earth export expenses and thereby enhances the economics of utilizing the Moon. From a purely scientific point of view, it is likely that the anhydrous strengthening phenomenon will have numerous implications for a wide range of geological and other scientific investigations on the Moon in which mechanical properties play an important role.

Acknowledgments *I would like to acknowledge helpful discussions with* I. *Clemens R Dick, E Mathez M. Rovetta,* I *Rowley, and* T. *Shankland.*

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Folded aluminum floors. Here, the floors use all aluminum lightweight components. Folded aluminum sheet material with a deep section for high strength/weight ratio can be fabricated with a profile to permit "nesting' for transportation The maximum length of components is determined by payload bay space dimensions of the transport vehicle. This floor system of terrestrial manufacture would be used for the initial sections of the shield. Later, with a production plant installed, moulded regolith components would be produced for the floors.

Pneumatic component *floors* These would employ inflatable beams, which have been successfully used for bridges in military application to carry trucks and tanks over gullies and craters. They consist of large-diameter inflated long tubes, smaller cross tubes, etc., wlth an aluminum deck over all. This floor system of terrestrial manufacture would also be used for initial sections of the shield.

Low Arch Shield, Pressurized Enclosures Beneath (Figs. 3,4)

If the structure supporting the regolith is a low arch working in compression with no tensile stresses, then no reinforcement is required. Components of such an arch can be made of moulded regolith, assembled over a movable pneumatic support form. The arches are assembled in sections, each the wldth of the form, embracing several rings of components. After one section is in place and covered with regolith, the form is partially deflated and moved forward to assemble a new arch section.

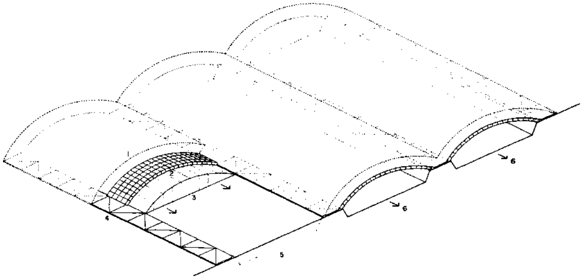

Figure *3.* BASE CONCEPT II. Low arch shield using moulded regolith components assembled over temporary, movable pneumatic support *form,* pressurized enclosures beneath. *General view of have. (1) Regolith shielding* *(2)* Interlocking moulded *regolith* arch *components All components identical dimensions (3) Movable pneumatic form supporting arch assembly (4) Aluminum lattice girders to accommodate outward thrust of arches Girders assembled flat on* surface *with* short *components and* anchored *to surface with vertical* pins *connected with transverse cables* at convenient *widely* space intervals *(5) Height increased* where *required by excavation .. (6) Expansion.*

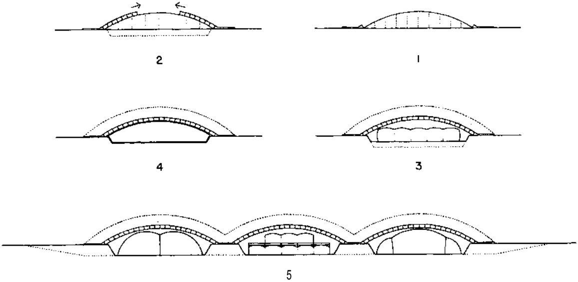

Figure 4. BASE CONCEPT 11. (See Fig 3). *(I) Inflated arch support form. (2) Interlocking moulded arch components laid* over inflated form. *(3) Regolith pushed overarch, pneumatic underneath where required by dragline scoop and pressurized enclosures erected.* (4) Alternative pressurized *enclosure using hermetic membrane applied to inner surface of shield. (5) Interconnected arch shields with range of pressurized enclosures*

The thrust of the arch is horizontal and is accommodated by two aluminum lattice girders conveniently assembled from short sections flat on a level surface, one on each side of the arch. The girders are anchored by pins driven into the lunar surface or by transverse connecting cables. All the girders are conveniently deep, and cables can be widely spaced. As in the first concept, initial sections of the arch can be quickly assembled using terrestrially manufactured components to provide immediate radiation protection. These components could be of folded aluminum or plastic with a profile that permits "nesting" for compact and economic transportation.

The weight and size of the prestressed floors and compression arch shield structures using moulded regolith components will be determined by the lifting capacity of one or two persons or equipment, as well as the moulding technique. The design of the components will employ a thin-rib, deep-section configuration to maximize stiffness and minimize weight. Components will be interlocking both transversely and longitudinally and self-aligning under stress. They will be manufactured in a lunar plant from presorted regolith, formed accurately to the required configuration through moulding, either by firing to the necessary temperature for sintering and surface sealing using a direct solar or electrical furnace, or by using a double-mix epoxy or portland-type cement to bond regolith aggregates.

Low Arch Shield with Pneumatic Support Structure (Fig. 5)

In this concept, a pneumatic structure permanently supports the regolith. The deflated structure is laid on a leveled surface, regolith is pushed over, and the structure is inflated.

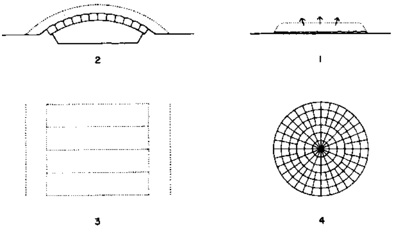

Figure 5. BASE CONCEPT III. Low arch shield with pneumatic support structure. *Deflated pneumatic* hybrid structure *flat on ground,* regolith pushed *over. (2)* Structure *inflated, raising the regolith, afterwards evened out or thickened* where *necessary. (3) Plan showing the concept* applied *in sections for a continuous low arch shield. (4)* Plan *showing concept applied in a low, domed shield.*

The raised regolith is evened out afterward or thickened where necessary. The upper surface of the structure is ribbed to anchor into the regolith. This concept can be applied in sections to form a continuous low arch or a single domed structure.

ARCHED AND DOMED SHIELD SUPPORT STRUCTURES

Arches or domes must be fairly flat since regolith cannot be placed on curved sides that rise too vertically. The dome form can be erected without supporting formwork for most, but not all, of its height, if the courses are raised equally all around the perimeter. However, this dome form must be almost a hemisphere with steep sides that are difficult to cover and that have excessive middle height, making it inconvenient to use. Another considerable disadvantage of the dome is that many components (a dome will have thousands) will have different dimensions, greatly complicating component moulding. In contrast, the low arch form would have only slightly inclined sides, so that regolith can be easily pushed over it, and all building components are dimensionally identical. Also, the arch form can be very conveniently expanded lengthwise.

PRESSURIZED ENCLOSURES AND PNEUMATIC STRUCTURES

Pneumatic structures under shielding canopies can be of three types: air supported, air inflated, and hybrid. Each would need to be evaluated for lunar application. The *air-supported* structure has one structural membrane supported by the push of internal pressure. The *air-inflated* structure has beams, columns, and arches that are independently pressurized and that support membranes between them. The two concepts are combined in *hybrid* structures making this type particularly attractive for lunar applications. Cable mesh containment technique gives the advantage of special shaping and additional membrane support for accommodating higher stresses in the lunar vacuum environment. Rigid elements could be incorporated in the membranes to obtain stiffening, flattening, curving, sealing, mounting, etc.

Pneumatic structures have good potential for lunar application in combination with shielding canopies, especially for the initial building thrust after the post-camp stage.

They are small in volume and light in weight, can be formed in a wide range of shapes, and can provide environments at a range of pressures. A great deal of design work and technical experience covering work done over more than 40 years is available in this specialized technology area. Since about 1950, thousands of small and large structures have been erected in many countries for many uses. Recent advances in flexible plastic material with very high strength/weight ratios make pneumatic structures particularly attractive for lunar application under radiation shielding.

SUNKEN AND BERMED STRUCTURES

These could accommodate smaller spans and spaces of the lunar base. To avoid the need for a heavy conventional excavator, lightweight equipment most be fully evaluated, particularly dragline techniques. In a lunar application a dragline would consist of continuous cables with attached scoops running over one motorized and one free vertical capstan. The dragline would run continuously with minimum attendance to excavate trenches of any depth or width. Shielding platforms of any of the types discussed would be erected in the trenches and the loose regolith pushed over to the required thickness. Pneumatic structures would afterwards be inflated beneath the platforms. The use of dragline technique would suggest a linear base arrangement, and the powered capstan could afterward be used as a transportation spine and system.

Each of these concepts has merits and weak points. The design that combines regolith directly on a pneumatic support structure has the disadvantage that if a reduction in pressure is experienced, the shield will drop and crush the contents underneath. There is the risk of failure in the other proposals, but independent, pressurized enclosures may protect their contents and support a failed shield.

SOLAR SHADING CANOPIES

Canopies are proposed to create partial or complete shade over walkways or vehicular driveways linking different parts of the base that for safety or functional reasons must be separated from the main base shield. A horizontal canopy would give total shade at lunar noon. Temperature in the canopy shade would depend upon the width of the canopy, since radiative thermal transfer or conduction via the ground will occur at the edges. Solar shade with low temperature means that personnel moving under the canopies by walking or vehicle need not be suited for cooling, but only for pressure.

Canopies might be perforated with small holes to permit the passage of some light as a fine pattern. This would slightly raise the temperature of any intercepting surface, the intensity depending upon the size oldie perforations in the canopy.

The feasibility of lightweight, portable or mobile shading canopies must be studied. These could be placed on the lunar surface where and as required: for servicing the plant, vehicles, mining operations, construction, etc. Personnel working on these tasks could possibly have more freedom of movement and greater work range and duration with lighter suits.

SERVICE STATIONS

The distance a person can travel wlll be limited by radiation exposure time on the lunar surface. Any long distance travel by relatively slow moving vehicles is difficult to envisage. To undertake long distance movement, shielded service stations must be built at strategic spacing for radiation-free resting and sleeping environments, supplies, servicing, etc. They would also offer emergency shelter at the time of increased radiation that comes with solar flares, generally predictable in advance, for persons some distance from the main base. Ideally, surface vehicles for long distance travel must be developed with radiation shielding.

SOLAR ORIENTATION

This might be a very important determinant in the layout of the base, or parts of it. As the sunsets and sunrises are relatively long and low-angled, energy build-up on vertical or steeply inclined surfaces might be considerable; this problem should be studied in base layout and design. Entrances and external operational edges of the complex should be orientated away from the sun to minimize temperatures at these points. Also, vertical surfaces, perhaps in combination with horizontal ones, could be developed to provide shade where needed.

INTERIOR ENVIRONMENT

The psychology of interior space and treatment in sealed environments is an important aspect of the base design. The mental stability and vitality of base inhabitants is an essential factor and will be influenced by interior design. Experience from sealed environments, such as in submarines, some industrial complexes, tunnels, *etc.,* must be fully evaluated for possible application in the lunar context

RESEARCH AREAS

If the lunar base is to be on line by 1995, research and development must be initiated in the near future. The main technology and engineering issues generated by the base concepts and for which terrestrial based testing, development, and research work must be done include the following:

1. Regolith should be tested for moulding building components using heat, sintering, and sealing. Lunar-based experiments are needed for a simple solar furnace.
2. Regolith moulding using bonding agents and cementitious materials such as portland cements and double mix epoxies needs testing in terrestrially based vacuum experiments.
3. Regolith potentiat for glass and ceramic building materials should be determined. Increased strength of materials in an anhydrous lunar environment should be evaluated.

4. Degradation of materials in a lunar environment should be studied, especially in such materials as plastic, including Kevlar, Teflon, and adhesives, and in metals, in particular, aluminum variants. There is a need for radiation/vacuum exposure experiments.

5. Physical movement of materials following wide diurnal temperature changes should be tested, as should regolithic ceramic-based components, plastics, etc.

6. The shape and size of components for compression arch shields and their assembly should be modeled and tested, along with interlocking joints and component profiles.

7. The shape and size of components for prestressed flat shields and their assembly should be modeled and tested.

8. Pneumatic, pressurized envelopes in a wide range of shapes and sizes using Kevlar, Teflon, and steel cable materials should be tested. Net as a structural element, containing and shaping an internal pressure membrane, could be researched. A technique for generating a range of shapes should be developed.

9. The initial stage of the base and community layout should be planned for expansion. Options should be diagrammed and analyzed.

10. The influence of transportation on community layout should be studied, with emphasis on a linear transport route for moving people and goods, shielded or unshielded, pressurized or not. Connections to other parts of the base could be diagrammed and options analyzed

11. The influence of solar orientation on community layout should be tested with models and a solar simulator. Glare and thermal gain must be minimized.

12. Shaded canopies linking separate parts of the base should be modeled and tested with a solar simulator. Both vertical and horizontal shades should be studied; perforated shades should also be studied

13. Trenching methods for excavation should be studied using dragline techniques: a rotating cable with scoops travelling around two or more surface capstans. Its influence on base layout and possible later use for transport should be considered.

14. Inside/outside air-lock/valve design for equipment and vehicles as well as individuals should be researched with attention to physical convenience, dust filtration, pressure leaks, and various sizes.

15. The psychological aspects of interior design should be studied, since emotional stability can be influenced by human-related dimensions, color, textures, etc

FORM AND FUNCTION IN LUNAR BASE DEVELOPMENT

Functional considerations will determine the width, height, span, and areas of the various functional components of the lunar base (which need to be more precisely defined). As yet, we do not have specifications and dimensions for the range of anticipated base functions. A small base planning group should be formed to work in close collaboration with all specialized areas of the lunar base group to determine the dimensional characteristics of the base functions with their environmental and servicing needs. The functional inventory will influence the base design, but the ultimate design will also be affected by the building system and shape(s) decided upon.

CONCRETE FOR LUNAR BASE CONSTRUCTION

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Prior to the establishment of lunar scientific and industrial projects envisioned by the National Aeronautics and Space Administration, suitably shielded structures to house facilities and personnel must be built on the Moon. One potential material for the construction is concrete. Concrete is a versatile building material, capable of withstanding the effects of extreme temperatures, solar wind, radiation, cosmic rays, and micrometeorites. This paper examines data published by NASA on lunar soils and rocks for use as concrete aggregates and as possible raw materials for producing cement and water, and investigates the technical and economic feasibility of constructing self-growth lunar bases A hypothetical 3-stoty, cylindrical concrete building with a diameter of 210 ft 164 m) was analyzed for conditions of a vacuum environment, lunar gravity, lunar temperature variations, and I atmosphere intemal pressure The advantages of concrete lunar bases are subsequently discussed.

INTRODUCTION

A project proposed within the National Aeronautics and Space Administration to build permanent lunar bases after the turn of the century has drawn tremendous interest from scientific and engineering communities across the nation. Lunar bases will enable mankind to extend civilization from Earth to the Moon. Ample solar energy, low gravitational force, and abundant minerals on the Moon will provide excellent conditions for the development of scientific and industrial space activities. Prior to the establishment of these activities, suitably shielded lunar structures must be built to house facilities and to protect personnel from the effects of solar wind, radiation, cosmic rays, and micrometeorites.

As a material capable of withstanding these effects, concrete is proposed for construction and can be produced largely from lunar materials. This discussion covers the process of making cement from lunar material, concrete mixing in a lunar environment, physical properties of concrete at lunar surface temperatures, and structural design suitable to lunar conditions.

CEMENTITIOUS MATERIALS

Cements used in construction on Earth are made basically with raw materials such as limestone, clay, and iron ore. A burning process transforms the raw materials into primarily calcium-silicate pebbles called clinker. The clinker is then ground into micron-sized particles known as cement A wide variety of cements are used in construction. The chemical compositions of these cements can be quite diverse, but by far the greatest amount of concrete used today is made with portland cements. A typical portland cement

(Mindess and Young, 1981) consists of about 65% calcium oxide (CaO), 23% silica (SiO_o), 4% alumina ($A1_5O_3$), and small percentages of other inorganic compounds. Among these conslituents, calcium oxide is the most important in the cement manufacture.

Other types of cements produced with lower calcium oxide content are available, eg., slag cement, expansive cement, alumina cement, and low calcium silicate cement. High alumina cement has 36% calcium oxide while low calcium silicate cement has only 30% (78kashima and Amano, 1960). Theoretically, a cementitious material can be made with any proportion of $CaOSiO_0Al_iO_3$ that falls within the calcium-silica-alumina phase diagram.

LUNAR MATERIALS

Information from Apollo lunar soils and rocks indicates that most lunar materials consist of sufficient amounts of silicate, alumina, and calcium oxide for possible production of cementitious material. Table 1 shows the chemical compositions of some selected lunar samples (Morris, 1983; Ryder and Norman, 1980; Fruland, 1981). It appears that the content of calcium oxide in lunar material is relatively low in comparison with other major cement ingredients; our discussion, therefore, will center around the calcium oxides.

'abte 1. Chemical Compositions of Selected Lunar Samples

	*Major*Elements, *wt* %				
Element	Mare Soil (10002)	Hlghland Soil (67700)	Basalt Rock (60335)	Anorthosite Rock (60015)	Glass (60095)
$5i0_5$	42.16	44.77	46.00	44.00	44.87
$A1_50_3$	13.60	28.48	24.90	36.00	25.48
CaO	11.94	16.87	14.30	19.00	14.52
FeO	15.34	4.17	4.70	0.35	5.75
MgO	7.76	4.92	8.10	0.30	8.11
710_1	7.75	0.44	0.61	0.02	0.51
Cr_00_3	0.30	0.00	0.13	0.01	0.14
MnO	0.20	0.06	0.07	0.01	0.07
$5a_3O$	0.47	0.52	0.57	0.04	0.28

A review of available literature on Apollo lunar samples reveals that a typical mare soil has a CaO content of nearly 12% by weight, highland soil 17%, basalt rocks 14%, and anorthosite rocks, a calcium-rich plagioclase in the feldspar group, almost 19%. A rock type with 1996 CaO content is a good candidate for lunar cement production. Lunar sample 60015, a coherent, shock-melted anorthosite rock, is an example. The rock is approximately 12 x 10 x 10 cm and is largely coated with a vesicular glass up to 1 cm thick, as shown in Fig. 1. The glass layer has been interpreted as a quenched liquid derived from melting the surface layer of the anorthosite rock. Quenched glass generally is an amorphous substance and represents a potential cementitious material if ground to fine particle size.

Figure 1. *Pristine* anorthosite glass-coated *sample* 60015.

Glasses are common in lunar soils. Table 2 shows the averaged glass contents in lunar samples brought back by the Apollo missions Note that samples taken from Shorty Crater rims have glass content as high as 92.3%. The chemical compositions of glass could possibly be similar to glass sample 60095 shown in Table I.

Table 2. Average Glass Con tent of Lunar Samples

Mission	Average Glass Content, %
Apollo 11	6.6
Apollo 12	18.0
Apollo 14	12.2
Apollo 15	29.4
Apollo 16	10.6
Apollo 17	31.1

PROCESS METHODS

Figure 2 shows condensation temperatures of various elements in basalt rocks (Wood, 1975). Interestingly, all cementitious elements including ca, AI, Si, Mg, and Fe have condensation temperatures about 1400 K, at least 200° higher than those of non-cementitious elements. This unique physical property may enable us to separate cementitious elements from non-cementitious ones in the process of cement manufacture.

However, a temperature of 3000 K or higher will be needed for the elemental evaporation in the process. This may cause some degree of difficulty in finding suitable material for containment use.

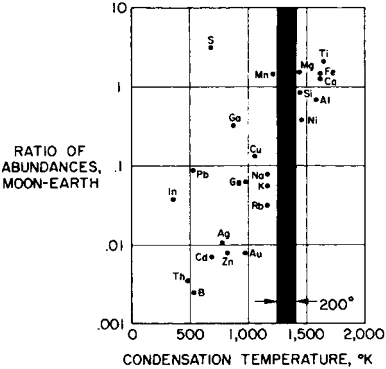


Figure 2. *Condensation temperature of basalt minerals*

Figure 3 shows residual fractions of multicomponent melt consisting of FeO, MgO, SiO_2, and Al_2O_3, of solar elemental abundances during the evaporation process at temperatures up to 2000°C (Hashimoto, 1983). The complete evaporation of FeO in Stage t may be utilized for metallic iron beneficiation. The remaining residues in Stage IV have high concentrations of CaO and Al_2O_3, and a small amount of SiO_2. Calculated proportions of the combined residues at lines A and B of Fig. 3 fall in the stoichiometric range of commercial high alumina cement (Lea, 1971).

AGGREGATES

Aggregates generally occupy about 75% by weight of the concrete and greatly influence concrete properties. Aggregates, according to American Standard for Testing and Materials (ASTM), are not generally classified by mineralogy. The simplest and most useful classification is based on specific gravity. Lunar soils and rocks all have specific gravities higher than 2.6 and are believed to be quality material for aggregate use. To produce concrete on the Moon, lunar rocks can be crushed to suitable coarse aggregate size, and the abundant lunar soils can be sieved to good gradation of fine aggregates.

Glassy soils used as aggregates may develop alkali-aggregate reactions that could cause the concrete to crack or spall . The lunar materials have never been exposed to oxygen and water, and the chemical and physical stability of these materials when exposed to water are not yet fully known. Research on lunar soil for possible aggregate application is indeed important

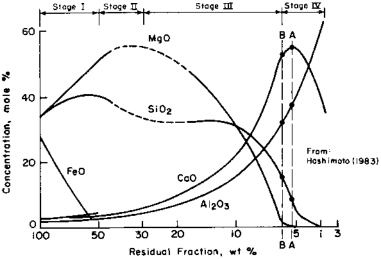


Figure 3. Change *of composition of residual molten* oxide *material* as *a charge is vaporized away into a vacuum, at* 2073 K

CHEMICAL COMPOSITION, WEIGHT PERCENT			
Compound	Solar Elemental Abundances		t
	A	@ B-B	
CaO	42?	40.0	36-42
2	52.3	48.8	36-51
[illegible]	5.0	11.0	4-9

WATER PRODUCTION

There have been studies on oxygen and metal production using lunar materials. Proposed methods include an alkali-hydroxide-based scheme (Cutler, 1984), hydrogen reduction of ilmenite (Agosto, 1984), and others. The ilmenite reduction reaction yields iron and water.

$$\underset{\text{ilmenite}}{FeTiO_3} + H_2 \;—\; TiO_2 + \underset{\text{iron}}{Fe} + \underset{\text{water}}{H_2 0}$$

Hydrogen is not readily available on the Moon and may have to be imported from Earth. The terrestrial hydrogen can be transported in the form of liquid hydrogen (H_2), methane (CH_4), or ammonia (NH_3) (Friedlander, 1984). In considering the need for carbon and nitrogen for life support and the higher boiling points of methane at -322°F (-161°C) and ammonia at -91°F (-33°C) than liquid hydrogen at -486°F (-252°C), it may be more advantageous to import methane and ammonia to the Moon rather than liquid hydrogen

REINFORCED CONCRETE

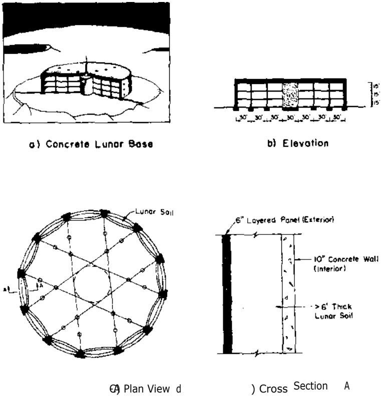
Concrete is basically a mixture of two components: aggregate and cement paste. The paste, comprised of cement and water, binds the aggregate into a rock-like mass as it hardens.

The flexural strength of plain concrete is generally low, about one-tenth of its compressive strength. However, concrete reinforced with either steel or glass fibers has increased flexural strength, strain energy capacity, and ductility. Test data reveal that concrete reinforced wlth 4% by weight of steel fibers possesses nearly twice the flexural strength of plain concrete (Hanna, 1977). These fibers act as crack arresters, that is, the fibers restrict the growth of microcracks in concrete.

STRUCTURAL DESIGN

Design of structures for a lunar base differs from design of structures on Earth. First, there are no wind and earthquake loads on the Moon. Second, the lower lunar gravity, one-sixth that of Earth, could permit an increase in the span length of a flexural member to 2.4 times, based on the flexural theory of a simply supported beam.

Figure 4 shows a proposed three-level concrete structure wlth a diameter of 210 ft (64 m). The structure is assumed to be subjected to 1 atmosphere pressure inside



a) Concrete Lunar Base

b) Elevation

ⒸA) Plan View d

) Cross Section A

Figure 4. Proposed three-level concrete lunar base.

and vacuum outside. The cylindrical tank at the center of the system serves as a safety shelter for inhabitants in case the system suffers damage or air leak It could also serve as a "storm cellar" during solar flares. The roof will be covered with lunar soil of suitable thickness 6-18 ft (2-6 m) (Arnold and Duke, 1978) to protect personnel and facilities from harmful effects of cosmic radiation.

Plain concrete is normally weak in tension but strong in compression Conceivably, the major demand on the structural system will be the high tensile stresses in the wall resulting from the internal pressure. To solve the problem, use of circular panels facing outward and supported by columns will change the tension into compression (Fig. 4c). Steel tendons can then be used to secure the columns into position. For effective use, these tendons could be placed around the cylindrical tank, stressed to provide hoop forces on the tank, and then anchored to columns at the opposite side. The 6-inch-thick (15 cm) layered panels at external faces of the wall (Fig. 4d) are non-load-bearing units. They are used to contain the soil between the internal and external panels. A layered system that is free to expand can minimize the thermal stresses due to extreme temperature changes on the Moon.

The proposed concrete lunar base structure has 90,000 ft' (8,360 m) of usable area. Approximately 250 tons of steel and 12,200 tons of concrete would be needed for the construction. That much concrete requires approximately 1,500 tons of cement and 490 tons of water. All these materials can be obtained on the Moon except hydrogen. The needed hydrogen from Earth is about 55 tons.

ADVANTAGES OF A CONCRETE LUNAR BASE

Concrete lunar bases offer the following advantages:

1. Economic. Table 3 compares energy requirements for four major construction materials (Mindess and Young, 1981). To produce I m^3 of aluminum alloy requires 360 GJ energy; 1 m^3 of mild steel requires 300 GJ; 1 m^3 of glass requires 50 GJ; and I m' of concrete requires 4 GJ. The energy ratio between aluminum alloy and concrete is 90:1. Less energy requirement in the production can be translated into lower cost.

Table 3. Typical Properties of construction Materials

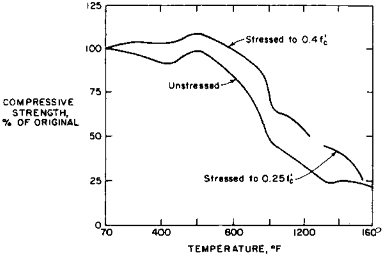
Materials	(1O^{6}/°q	k (W/m Kl	(G1/m^{3})
Aluminum Alloy	23	125	360
Mild Steel	12	50	300
Glass	6	3	50
Concrete	10	3	34 (4.01'

•$x_2$0 is made from ilmenite

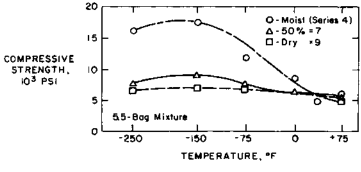
2. Compartmentalization. One major advantage of concrete is that it can be cast into any monolithic configuration. A lunar structure could be compartmentalized to prevent catastrophic destructlon in case of any local damage.

3. Concrete Strength. Lunar surface temperature may vary from -250°F (-150°C) in the dark to +250°F (120°C) facing the sun. Figure 5 shows that the strength of heated concrete is practically unaffected by 250°F (120°C) (Abrams, 1973). Concrete maintained at 75% relative humidity and temperature of -150°F (-100°C) increases in strength two and one-half times that of concrete maintained at room temperature, and two times at -250°F (-150°C). Concrete that has 0% relative humidity neither gains nor loses the strength in the course of the cooling period, down to -250°F (-150°C) (Montage and Lentz, 1962).

4. Heat Resistance. Concrete is thermally stable up to 1100°F (600°C). The low thermal conductivity as shown in Table 3 and high specific heat make concrete an excellent heat resistant construction material.



a) High Temperature Effect



b) Low Temperature Effect

Figure 5. Effect of temperature on compressive strength of siliceous aggregate concrete.

5. Radiation Shielding. Most radiation energy will be converted into heat energy in the course of attenuation in an exposed body. In general, a hardened concrete consists of 95% aggregate and cement and 5% water by weight Both aggregate and cement are non-metallic and inorganic, and are excellent materials for absorbing gamma-ray energy. Water is the best substance for absorbing neutron energy (D. S. Scientific Laboratory, 1950).

6. Abrasion Resistance. Micrometeorites can strike the Moon wlth relative speeds up to 25 miles/s (40 km/s). These microparticles may abrade the surface of the lunar structures. Concrete possesses high abrasion resistance, which increases proportionally with concrete strength

7. Effect of Vacuum. Exposed to the lunar environment, the free moisture in concrete may eventually evaporate, but the chemicatly bonded water will not. Again, Fig. 5 shows that the loss of free moisture, which generally takes place around 212°F (100°C) has no adverse effect on concrete strength.

A pressurized concrete structure may not be completely airtight. To solve this problem, an epoxy coating, or another sealant that hardens without oxidation, can be applied on the internal surface.

CONCLUSION

Reinforced concrete has many material and structural merits for the proposed lunar base construction. The attractiveness of this proposal lies in the fact that most of the components of the concrete can be produced simply from lunar materials. The scenario for the self-growth lunar base is as follows:

1. Materials: Cement could be obtained by high-temperature processing of lunar rocks. Aggregates would be obtained by physical processing of lunar rocks and soils. Lunar ilmenite would be heated with terrestrial hydrogen to form water, while the residual iron could be processed into fibers, wire, and bars for reinforcement
2. Concrete Casting and curing chambers for concrete could be developed from empty shuttle fuel tanks. Temperature and humidity control, as well as controlled drying and recycling of excess water, are vital parameters because water is an expensive commodity in space.
3. Construction: The evaluation of the most suitable structural design must include considerations of constructability. It is possible to optimize the concrete properties in order to achleve the most suitable design, both for ease of construction and for maintenance-free service.

Conceivably, concrete lunar bases will be essential facilities for the scientific and industrial developments on the Moon. Perhaps concrete will provide the ultimate solution to the colonization of outer space. The task of constructing lunar bases is a great challenge to scientists and engineers in this fascinating space age.

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CONCRETE AND OTHER CEMENT-BASED COMPOSITES FOR LUNAR BASE CONSTRUCTION

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The use of concrete and other materials based on a cementitious matrix is evaluated for the construction of a manned space station on the Moon Consideration is given to the most recent developments in the science and technology of cementitious materials and the feasibility *of in situ* construction using lunar materials. It is concluded that concrete construction on the Moon should be technically feasible.

INTRODUCTION

Recently it has been suggested (Lin, 1984) that concrete could be successfully used in the construction of a lunar base. This exotic use for such a mundane material seems at first sight impracticable. We associate concrete with massive structures involving the use of structural elements with large cross-sections that require large volumes of concrete. When we look at typical concrete properties (table I) we are still more convinced of the inappropriateness of concrete on the Moon. It is relatively weak, even in compression, and also fails in a brittle manner, so that tensile steel is required as reinforcement. It suffers from dimensional instabilities and various durability problems, as any highway traveller can testify.

The wide popularity of concrete, however, indicates that it has important advantages that outweigh the problems cited above. A major advantage is versatility. Concrete can be cast in almost any shape imaginable: witness the famous Sidney Opera House in Australia, or the Bahai temple now under construction in India (Anonymous, 1984). Furthermore, by a suitable choice of constituent materials and their proportions, concrete can be manufactured to exact and unique specifications for any given application. Another dominant advantage is economy: large masses of concrete can be produced cheaply

Table 1. Typical Properties of Conventional Concrete

	Normal Strength	High Strength
Compressive Strength	5000psi (35MPa)	12,000psi (85MPa)
Flexural Strength	800psi (6MPal	1300psi (9MPa)
Tensile Strength	500psi (3.5MPa)	800psi (6MPa)
Modulus of Elasticity	4×10^{6} psi (28GPa)	5×10^{6}(35GPa)
Strain at Failure	0.002	0.003
Drying Shrinkage	0.05-0.1%	0.05-0.1%

because concrete is made from inexpensive ingredients obtained primarily from local sources. This was one of the major assumptions of tin's (1984) proposal: that concrete can probably be made from lunar materials, thereby avoiding the costly alternative of transporting construction materials from Earth.

Economy is relative, however. If large quantities of concrete are required, the costs of mining, processing, and fabrication on the Moon may exceed the costs of ferrying lightweight prefabricated components made from steel or plastics from Earth. Continuing developments in concrete technology have led to high strength concrete two to three times stronger than conventional concrete. Such concretes can be used to produce structures of lower mass, and they also have better overall performance, since strength is an indicator of the quality of the concrete. Concrete with 14,000 psi (100 MPa) compressive strength can now be produced under field conditions (Burge, 1983; Radjy and Loeland, 1985), while special cementitious systems have been developed whose strengths are at least double the above figure (Hirsch *et al.,* 1983; Young, 1985). Since these materials do not use large-sized aggregates (particulate fillers) they cannot be considered concretes in the conventional sense, so 1 refer to them as cement-based materials. They not only have the potential to make a large impact on the economics of future lunar construction, but are also likely to be more suitable for the lunar environment.

Lunar base construction is an interesting materials problem for which there are several possible solutions. Lin (1984) sought to highlight the potential for concrete-based lunar structures, and in this paper 1 will examine the feasibility of his approach in light of the most recent developments of cement-based systems. I will be concerned only with the materials aspects; further development of structural designs is a separate problem whose solution depends on the decisions made with regard to a set of optimum material properties.

NEW CEMENT-BASED MATERIALS

Dr. Lin's structural design, while quite an elegant solution to the problem, assumes conventional concrete properties; he is considering a brittle material with only modest strength (up to 10,000 psi [70 MPa] in compression). His preliminary design called for 10-in thick precast sections, which represents quite a large mass in the lunar structure. Although transportation from Earth is eliminated by using lunar resources wherever possible, it must be assumed that mining and processing will still be expensive. Thus, reduction in mass would be desirable, but is possible only with a greater improvement in concrete performance.

As mentioned above, high performance cement-based composites have been developed during the last few years and are now entering the market place. These composites are attaining compressive strengths in the range of 30,000-40,000 psi (200-300 MPa), and, when reinforced with fibers, they can exhibit good ductility. Two distinct approaches have been taken, leading to MDF and DSP cements, as described below. Further evaluation of their properties and improved versions of these materials can be anticipated over the next few years.

Table 2. Typical Mechanical Properties of High Performance Cement-Based Materials.

	MDF Cement Paste	DSP Cement Paste
Compressive Strength, MPa	300	250
Flexural Strength, MPa	150	4
Modulus of Elasticity, GPa	50	40
Strain at Failure	—	0.003
Fracture Energy, J/m^2	200	40
Critical Stress Intensity Factor, Mpa.m^(1/2)	3	0.3

MDF (Macro-Defect-Free) cements were developed and named by Birchall and co-workers (Birchall *et al.,* 1982; Birchall, 1983; Alford and Birchall, 1985; Kendall *et al.,* 1983; Kendall and Birchall, 1985). The approach is to apply new processing techniques to the creation of the paste (cement + water) that forms the binding matrix in the composite. A water-soluble polymer is added as a processing aid, and only small quantities of water are used The Earth-dry formulation is mixed under high shear, during which the polymer prevents excessive entrapment of air by cavitation and provides cohesiveness and plasticity. The blended dough can now be roll-mixed (calendered) to eliminate residual entrapped air bubbles (the macro-defects). The plastic dough is readily molded into the desired shapes by extrusion, pressing, or other conventional plastics processing operation. The material is moist-cured at 80°C followed by air drying; a combination of cement hydration and polymer dehydration during this regime densifies the matrix. The properties of MDF pastes are impressive, as can be seen in Table 2, although as yet we do not fully understand the fundamentals of the material. The ratio of compressive strength to flexural strengths strongly suggests that the polymer is not simply a processing aid, but is actively contributing to the engineering properties. Portland cement has been successfully replaced by calcium aluminate cement (which actually appears to perform better).

DSP cements, which were conceived by Bache (1981), represent a quite different approach, since they were designed to be tastable, like concrete. This is done by control of the particle size distribution of the cement to minimize the void space between cement grains, which must be filled with water to make the system castable. As in the case of the MDF systems, the idea is to minimize the amount of water used in order to minimize the porosity of the final product, since material properties are always very strongly porosity dependent Bache added a very finely divided silica (particle size 0.1 pm), a by-product of silicon and silicon alloy production, to Portland cement in order to provide the void-filling capabilities. This material has the added advantage of reacting chemically with the cement paste to become an integral part of the cementitious matrix. A dispersing surfacant is also necessary to achieve castability. Later approaches to the DSP concept have used more than one addition for particle size control (Roy et *al.,* 1985; Wise *et* al., 1985). The properties of DSP materials are comparable to MDF pastes (see typical values in Table 2) except that they are much more brittle due to the absence of a polymer phase. DSP cements can also be formulated with calcium aluminate cements.

The structures of the paste matrix formed by both systems are quite similar at the micron level. Residual unhydrated grains of cement act as a "micro-aggregate" embedded in a matrix of hydration (reaction) products. The unhydrated cement makes up quite a large volume fraction of the paste, in contrast to cement paste in conventional concrete. We do not yet know the implications of this observation with regard to service performance. Fibers or fillers can be added to either matrix to achieve desired properties, such as ductility, abrasion resistance, etc.

These new materials are beginning to be used commercially as useful substitutes for metals or reinforced plastics. MDF composites can be drilled, tapped, or machined. They have been used *(Afford* and Birchall, 1985) in turntables and speaker cabinets for stereo systems, since the polymer imparts good acoustic properties. They are also being considered for ballistic protection and electromagnetic radiation screening. DSP composites are being used for press tools and molds in the aerospace and automotive industries (Wise *et al.,* 1985) where they replace metals and for machinery parts where abrasion resistance is of prime concern (Hjorth, 1983, 1984). DSP-based molds have been successfully used in vacuum forming (Wise et at, 1985). Such molds have been found to have lower vacuum leak rates than the aluminum molds that they replace.

It is clear from the above discussion that these advanced materials have the potential to provide structures of low mass (reduced cross-sections) to act as an air-tight radiation shield and with sufficient ductility and abrasion resistance to resist meteorite impacts. However, at present little is known about .the long-term properties of these materials: their response to large temperature fluctuations, strong drying, impact loadings, fatigue, prolonged vacuum, etc. An extensive evaluation program will be necessary to obtain this kind of information, although no doubt it will be gradually developed. Studies will need to be made on a variety of composites made with different combinations of cements, aggregates, and fibers.

LUNAR PRODUCTION OF MATERIALS

The potential for utilizing lunar resources for the constituents of cement-based composites is an attractive scenario. However, the manufacture of cement, which is a crucial step, will not be a straightforward problem. Both Portland cement and calcium aluminate cement contain over 60 wt % of CaO, whereas lunar rocks and soils are relatively low in CaO (<20 wt %). Limestones do not occur on the Moon. It is possible that a CaO enrichment scheme could be developed using differential vaporization (Agosto, 1984), but the economics may be prohibitive. Perhaps digestion by molten alkali hydroxides to break down minerals into their oxides (Cutler, 1984) might be feasible.

However, one should not be constrained by conventional cement chemistry. One could attempt to manipulate the existing chemical composition to provide a reactive material by fusion-recrystallization processes. Perhaps reactive glasses with a reactive solution, such as carbonic acid (Young et al., 1974) or a polyelectrolyte (Wilson, 1978,

1979) could be used, either of which can initiate very rapid reactions. Development of a suitable cementitious system may require some innovative approaches but should not be an insurmountable problem. It remains to be seen to what extent the strategies of the DSP and MDF systems could be successfully implemented if a new cement chemistry is adopted.

The question of suitable aggregates is much less critical. Processed Moon rocks should be satisfactory provided they are not excessively weak and there is a reasonable thermal match with the cementitious matrix. This is necessary to avoid the creation of internal stresses that could cause internal microcracking and loss of properties (e.g., vacuum tightness, abrasion resistance, *etc.).* Lack of moisture eliminates most durability problems encountered with aggregates on Earth, such as alkali-aggregate reactions or freeze-thaw distress. Whether lunar soil can be successfully used as aggregate will depend primarily on its fineness and particle characteristics. Since weathering does not occur, clay minerals should be absent, helping to reduce the potential water demand. It may be possible to use lunar soil as a densifying fraction in a DSP-type formulation.

Inorganic fibers—rock wool or glass, for example—could probably be made in situ, as could steel fibers using iron extracted from rocks. It might be economical to bring lightweight organic fibers (polypropylene, Kevlar, or carbon) from Earth, since the weight fractions needed to enhance ductility and resistance to cracking are quite low. Similarly organic compounds used in small quantities as processing aids might also be brought to the Moon economically.

The final ingredient is water, which must either be shipped in from Earth or synthesized on the Moon. It will therefore be a scarce and expensive commodity. This is an advantage technically, in that the manufacture or high performance concrete (or other cement-based composites) will now become the most attractive choice economically because less water would be used. One needs to carefully examine alternate hardening strategies that might not use water as the sole reactant, such as carbonation curing (Young *et al,* 1974; Goodbrake *et at,* 1979). Carbon dioxide could be obtained from the organic refuse of human activity. The actual water needed could be less than one quarter of that used in conventional concrete, especially if the water removed during drying is collected and recycled. Terrestrlal hydrogen burnt in oxygen extracted from Moon rocks (Friedlander, 1984) is the most likely source of water, although it may be possible to obtain some hydrogen on the Moon (Carter, 1984).

FABRICATION OF CONCRETE

Concrete will have to be formed into precast elements under controlled conditions of humidity and temperature. This is, of course, the key to the hardening process, as well as to maintaining the high level of quality control that will be essential. The "curing" process will involve not only promoting the chemical reactions required for strength development, but also subsequent drying to equilibrium with the lunar atmosphere. This involves much stronger drying than is normally encountered on Earth, but laboratory studies tell us what to expect. Drying shrinkage will be about 2-3 times the usual values and, unless developed very slowly, will cause cracking. Controlled drying may well be the most crucial part of the whole "curing" process and may dictate the choice of hardening strategies. Use of heat and concomitant carbonation would not only increase the rate of strength development, but would also provide a more dimensionally stable

CONCLUDING REMARKS

The goal of making concrete on the Moon is an intriguing challenge, one that can almost certainly be met technically. Concrete is truly a versatile material: when the tight economic restraints of terrestrial construction are removed, it will be possible to take advantage of methods and strategies that most engineers are not yet aware of The basic principles that would guide development are well established, although considerable research and development will still be needed to generate the necessary specific information

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GUIDE TO USING LUNAR SOIL AND SIMULANTS FOR EXPERIMENTATION

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The vision of a lunar base has stimulated experimentation needed for the planning and construction of lunar vehicles, habitats, and factories The following discussion is a gulde to facilitate the design and interpretation of technology experiments on lunar soil and lunar soil simulants. Lunar soil, once it is taken from the Moon for study in the laboratory, may not represent true *in situ* lunar conditions. The proposed simulated soils are different from genuine lunar soils in several important respects, mostly due to the effects of mlcrometeorites and solar wind on the Moon. However, these proposed simulants do replicate the lunar soil grain size distribution, grass mineralogy, and general chemical composition and are useful for studies of these properties. There are several reserves of lunar material that are suitable for tests requiring genuine lunar not.

INTRODUCTION

Past studies have concentrated on unlocking scientific secrets of lunar soil. Extracts of scientific studies on chemistry and petrography of the 163 individual soils and an extensive bibliography are found in *Handbook* of Lunar *Soils* (Morris et *al.,* 1983). A review of lunar soil petrography is given by Heiken (1975). Although lunar soil chemistry is fairly well known, engineering properties and industrial reactions are not as well studied.

Mechanics and thermal information on *in situ* soil conditions was gathered by early researchers from television, surface photography, and measurements using a penetrometer and heat flow probe. Observations on the lunar surface include the Apollo lunar module descent engine blowing dust, depths of footprints on crater rims, the rover throwing dirt in the "grand prix," drilling, trenching, scooping, and raking. *In situ* properties are most relevant to the use of lunar soil for tunneling, heaping, and excavating, and as a substrate for buildings and vehicles. The properties of interest are the *in situ* bulk density and porosity. For surface activities similar to those conducted on the Apollo missions, these properties are probably known well enough.

Other properties, intrinsic to the soil grains, become important for those experiments where lunar soil is an active ingredient in a process. These properties include composition, rock form (crystalline, glassy), grain size, grain shape, grain strength, grain surface reactivity, dielectric constant, and magnetic susceptibility. Present *interest* includes experiments for extracting oxygen from the soil, melting or chemically reacting the soil for use as structural material, and growing organisms on the soil.

BRIEF DESCRIPTION OF LUNAR SOIL

Lunar soil can be described in familiar terrestrial terms as well-graded silty sands or sandy silts with an average particle size by weight between 0.040 and 0.130 mm (Carrier et *al.,* 1973). The density of in *situ* bulk lunar soil, as determined from large diameter core tube samples, is typically 1.4 to 1.9 g/cm^3 . The bulk density increases with depth, and below 10-20 cm the soil is often at higher density than is required to support the overburden in lunar gravity (Carrier *et al.,* 1973). Spheres, angular shards, and fragile, reentrant, vesicular grains are among the diverse shapes found in most lunar soils. The most abundant particles composing the soil are igneous or breccia lithic grains, mineral grains, glass fragments, and the unique lunar agglutinates. Major lunar minerals are pyroxenes, anorthite, ilmenite, and olivine. Compositionally, the lunar soils fall into two broad groups: the highlands soils, which developed on anorthositic bedrock, and the mare soils, which developed on basaltic bedrock, The mare soils can be further subclassified as to high or low titanium content. Highlands soils are relatively enriched in aluminum and calcium, while mare soils are relatively enriched in iron, magnesium, and titanium. Average major element chemistry of these three types is given in Table 1.

Table I. Major Element Chemical Composition of Lunar Soils and Soil Simulants

	Lunar Highlands (%)	Lunar Low Titanium Mare Soils t (%)	Lunar High Titanium Mare Soils§ (%)	Hawaiian Basalt- - (%)	High Titanium Mare Simulant t (%)
Si%	*45.0*	*46.4*	42.0	46.4	41.7
	0.5	2.7	7.5	2.4	7.5
	272	13.5	13.9	142	12.8
$Fe20_3$	–	–	–	4.1	3.7
FeO	5.2	15.5	15.7	8.9	12.8
MgO	5.7	9.7	7.9	9.5	8.5
CaO	15.7	10.5	12.0	10.3	92
Total	99.3	98.3	99.0	95.8	962

*Average composition of Apollo 16 soils compiled from Handbook *of Lunar Soils* (Morris, 1983).

tAverage composition of Apollo 12 soils from Taylor (1975), p. 62.

lAverage composition of Apollo 11 soils from Taylor (1975), p. 62.

••Composition of Hawaiian basalt HAW-1 I from Basaltic *Volcanism on the* Terrestrial *Planets,* p. 166.

}Calculated composition from recipe in Table 2. Iron in ilmenite as FeO.

CHANGES IN SOIL FROM MOON TO LABORATORY

Soil cannot be removed from the surface of the Moon without altering at least some of the *in* situ characteristics such as bulk density and stratigraphy. The least physically disturbing way of sampling the lunar soil was with the large diameter core tubes used

Table 2. Changes in Soil from Moon to tab

	Conditions	Changes
Moon	Impact-derived particle packing High vacuum	
Curatorial Facility	Dry nitrogen	Loss of original packing Adsorb water (minor)
Laboratory	laboratory atmosphere	Adsorb water (major) Oxidation

on Apollo 15, 16, and 17 (Carrier *et al.,* 1971). Soil undergoes still further changes in the experimenter's laboratory (Table 2). On the lunar surface soil particles reside in a hard vacuum, free of water molecules and other atmospheric gases. The packing of particles is affected by continual meteorite bombardment The dominant effect of this pounding is to pack the soil more tightly, although occasionally soil particles on the surface are ejected and then settle to a less dense configuration on crater rims (Carrier, 1973).

In the lunar sample curatorial facility, "pristine" samples are stored and handled only under dry nitrogen. Even so, small amounts of water and other gases are probably adsorbed on the highly reactive surfaces of lunar soil grains. The soil grains have lost their original packing during excavation, transit to Earth, and laboratory handling.

Furthermore, the ambient atmosphere of the experimenter's laboratory, with its relatively high water vapor and oxygen content, causes much more water to be adsorbed on the grain surfaces and some oxidation to occur. For example, the abundant metallic iron in lunar soil rusts easily.

SOME CRITICAL DIFFERENCES BETWEEN SIMULANTS AND LUNAR SOIL

Solar radiation and meteorite impacts, large and small, alter soil grains in ways that are difficult to duplicate on Earth. Also, lunar minerals are compositionally different, on a minor scale, due to the lack of volatile elements and reduced amounts of oxygen when the minerals were formed. Some of these unique lunar characteristics can be reproduced in very small quantities of simulant in experimental guns, charged particle beams, or furnaces. However, it is not practical to make usable quantities of simulants by these methods. Since simulants will probably be made using crushed, naturally-occurring minerals, they will be different from true lunar soil in several ways (Table 3).

Agglutinates, Iron Metal

Since the Moon has no atmosphere, very small meteorites impact the soil at high velocity, melting and shocking the rocky soil grains. Evidence of an impact on a 1 mm

Table 3. How Successful is a Simulant?

Can Simulate	Difficult to Simulate
Grain size distribution	Agglutinate glass with dispersed metal, grain shape
Gross mineral composition	Solar wind nuclei implantation Shock effects (grain strength)
General chemical composition	Mineral chemistry (reduced elements, no hydration)

diameter glass sphere taken from lunar soil is shown in Fig. 1. The splatters of glass from many repetitions of such micrometeorite impacts can glue tiny grains together in convoluted structures called agglutinates (Fig. 2). Iron metal blebs of 10 nm diameter are distributed throughout the agglutinatic glass, making the glass magnetic. Agglutinates can make up over 50% of a mature lunar soil. This gluing together of smaller grains into larger ones is part of two competing processes, for impacts also break down soil grains into smaller ones.

Solar Wind

Because the Moon does not have a global magnetic field, high velocity nuclei from the solar wind impinge directly on small soil grains. These nuclei, of which hydrogen and helium are the most common, become implanted in the outer few angstroms of soil grains, creating an amorphous layer. In mature soils this solar wind hydrogen can exceed 100 ppm.

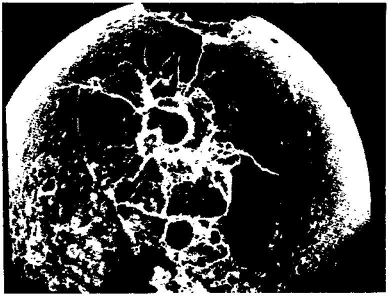

Figure I. One millimeter diameter lunar glass sphere with micrometeorite impact pit Photo courtesy of D. S McKay (

Figure 2. One millimeter diameter agglutinate Photo courtesy of D. S McKay (S-71-24575).

Shock Effects

The shock effects of meteorite impacts are commonly retained in lunar soil grains. Impacts fracture and weaken the mineral grains found in the lunar soil.

Mineral Chemistry

The major lunar minerals (anorthite, pyroxene, ilmenite, olivine) are similar in gross aspects to their terrestrial counterparts. However, the lunar minerals do not contain bound water in the crystal structure and have not been altered by hydration reactions on grain boundaries. Due to extremely low oxygen fugacities at the time of crystallization, several elements in lunar minerals are found in a more reduced state. Combined iron is almost totally ferrous iron, and iron metal may be found in interstitial phases and dispersed in glass. Titanium and chromium occur in the more reduced valence states of +3 and +2, respectively. Lunar ilmenite does not contain hematite as many terrestrial ilmenites do.

LUNAR FINES AS EXPERIMENTAL SAMPLES

Lunar samples are allocated very sparingly, and investigators are encouraged to work on the smallest possible samples. For example, scientific investigators typically determine major element chemistry from only 50 mg of material. Since engineering and industrial studies often require much larger sample size, experimenters must, when possible, scale down their experiments and make use of simulants.

Any lunar samples that may be available for technology studies will probably come from the residue of fines left in the Apollo collection bags. Early missions collected fewer, but larger, soil samples, On later missions, samples were smaller, more carefully chosen to sample different phenomena, and placed in individual bags.

Table 4. Grams of Sample Bag *Residues* from Apollo Missions

Apollo 11	55 g
Apollo 12	-
Apollo 14	225 g
Apollo 15	335 g
Apollo 16	1808 g
Apollo 17	3525 g
Total	5948 g

The residue of fine material remaining in the rock and soil sample bags (about 5 kg total) could be pooled and homogenized for each mission except Apollo 12 (4). This would result in a mixture of fines, representing an average chemical composition for each site of large enough size to serve as a standardized sample. However, these samples would not be representative of a true soil since rock dust would be admixed Soil maturity (degree of exposure to micrometeorites and solar wind), as determined by fine-grained metallic iron content (Morris, 1978), would give a general indication of proportion of soil to rock dust Investigators concerned with agglutinate, metal, and solar wind content could then make adjustments for under-representation of these components in the pooled fines.

As a standard sample, these pooled fines would be of known composition, grain size distribution, and maturity. This would be advantageous for comparisons among experiments. Use of these bag residues would be an efficient use of the Apollo collection, since their mixed origin makes them less valuable scientifically.

SIMULANTS FOR EXPERIMENTS

Since the properties to be simulated and degree of fidelity required are different for laboratory experimentation than for testing equipment and structures, simulants for these two uses are discussed separately. In general, simulants for laboratory experimentation require greater fidelity to chemical and mineral composition, in addition to grain size distribution. In creating simulants, costs must be weighed against benefits of increasing fidelity to lunar soil. The approach described below is a "middle-of-the-road" effort, when compared to the low cost extreme of using the nearest sand or crushed rock and the high cost extreme of creating micrometeorite impacts and solar wind implantations one by one in experimental guns and ion beams. Simulating the lunar soil for laboratory experimentation is approached from three aspects: soil grain size distribution, soil particle type distribution, and particle chemistry.

Grain Size Distribution

Grain size distribution curves have been compiled that encompass most Apollo soils (Carrier et al., 1973). The grain size distribution of simulants should be created with the fewest sieve sizes that adequately characterize the grain size distribution curve and yet are practical to use. Thus, simulant composition should be defined as 90% finer than

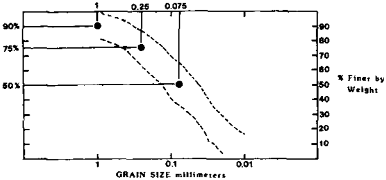

Figure 3. Grain site distribution curves encompassing most *Apollo soils Plot ond* data *adapted from Carrier* et at (19730 Percent *finer by weight* at sieve sites 1.0, 0.25, and 0075 *mm are used to define simulant characteristics*

1 mm, 75% finer than 0.250 mm, and 50% finer than 0.075 mm (Fig 3). The distribution curve is not precisely simulated below 0.075 mm, because it is impractical to sieve large volumes of rock below this limit Therefore, it is important to calibrate the pulverizing process in the small size range.

Particle Type Distribution

Nearly all particles comprising the lunar soil are lithic (chiefly breccia and poikilitic rocks in the highlands and breccia and basalt in the maria), mineral or glass fragments or agglutinates. The simulation is simplified by using crushed basalt or minerals to substitute for the lithic and mineral fragments and by using crushed glass to substitute for glass fragments and agglutinates. Although lunar particle type distribution varies with maturity of the soil, source rock type, and particle size, both mature highlands and mature mare soils can be approximated with a mineral or rock to glass ratio of l:l for sieve fraction <0.250 mm and a ratio of 3:1 for sieve fraction >0.250 mm. [These proportions were calculated from data for sample 60010 given in McKay et al. (1977) and from data for sample 71016 given in Heiken and McKay (1974).]

A Highlands Simulant

The target chemical composition for the highlands simulant is the average of Apollo 16 soils as given in Table 1. Normative calculations (Chayes and Metais, 1964), based only on Si, Al, Fe, Mg, and Ca indicate that a 3:1 weight ratio of anorthite (CaAI) to pyroxenes (of mixed composition) would approximate this chemical composition. Adding pyroxenes raises both the iron and magnesium content

Unaltered anorthite is not common on Earth. The least altered anorthite crystals can be found associated with frothy glass near some andesitic volcanoes, such as Miakejima near Tokyo. Anorthite also is found mixed with other minerals in andesitic areas and as anorthosite rock in layered intrusions, of which the Stillwater complex in Montana is an example.

The orthopyroxene bronzite is a close practical substitute for the norm-calculated pyroxene ratios of hypersthene (orthopyroxene) to diopside (clinopyroxene) of 6:1.

Glass of the highlands composition given in Table I can be made by Coming Glass Company by the dri-gauge method (Minkin et al, 1976).

In summary, a highlands simulant can be made by combining crushed anorthite, pyroxene, and synthetic glass in proportions based on grain size, lithic or glassy character, and chemistry. A sample recipe of this type is given in Table 5.

A High Titanium Mare Simulant

The target chemical composition for the high titanium mare simulant is the Apollo 11 soil average given in Table 1. The lithic and mineral component can be approximated by terrestrial basalts plus ilmenite. HAW-I I (Basaltic Volcanism Study Project, 1981), whose chemical composition is also given in Table 1, is an example of a suitable basalt Combining this basalt with ilmenite ($\mathrm{FeTlO_3}$) in a 9:1 proportion raises the titanium content of the mixture to that of the Apollo 11 soil. The resulting mixture also improves the calculated fit to Si, Fe, and Mg percentages of the Apollo soil (Table I).

Glass of high titanium mare composition can also be made from melting oxides. Naturally occurring, basaltic-composition volcanic glass, such as is found in Hawaii could be used, but probably will not have a titanium concentration as great as the high titanium mare soils.

In summary, a high titanium mare simulant can be made by combining crushed Hawaiian basalt HAW-II, ilmenite, and synthetic glass in proportions based on grain size, lithic or glassy character, and chemistry. A sample recipe of this type is given in Table 5.

SIMULANTS FOR TESTING EQUIPMENT AND STRUCTURES

Important parameters to simulate for testing equipment and structures include bulk density and porosity. Grains of correct size distribution and specific gravity are needed,

Table 5. Recipes for Lunar Soil Simulants

	Sample Highlands Simulant Anorthite to Pyroxene Ratio 3: <0.075 mm	0.075 to 0.25 mm	025 to 1.0 mm	>1.0 mm
Anorthite	18.8	9.4	8.4	5.6
Pyroxene	6.2	3.1	2.8	1.9
Glass	25.0	12.5	3.8	2.5
	Sample High Titanium Mare Simulant Basalt to ilmenite Ratio 9:1' <0.075 mm	0.075 to 0.25 mm	025 to 1.0 mm	>1.0 mm
Basalt	22.5	11.3	10.1	6.8
Ilmenite	25	12	1.1	0.7
Glass	25.0	12.5	3.8	2.5

'To make t00 g of simulant mix components by grams indicated in table.
The same grain size fractions and lithic to glass ratios were used for both simulants: >I ; 025-1 mm=0.15; 0.075-025 mm =0.25; <0.075 mm =0.50 (total = 1.00). The lithic to glass ratio for >025 mm =3:1 and for <0.25 mm =1:1.

so chemistry and mineralogy are less important. Also, since much larger quantities of simulant are needed (tons), crushing and grinding of a single component, usually basalt, on commercial size equipment would be used. Nearly 2500 kg of a basalt simulant was fabricated and characterized for testing the lunar rover (Mitchell and Houston, 1970; Green and Melzer, 1971). Crushed basalt also has been used for lunar resource utilization studies (Steurer, 1982).

The importance of packing the simulant properly after grinding is illustrated in the testing of the Apollo lunar surface drill by Martin Marietta. The simulant, used during design of the drill, was packed to a lesser density than was actually encountered on Apollo 15. The surprisingly dense soil at Hadley Rille made the drilling effort more difficult than expected. The density of the entire Apollo 15 drill sample was 1.75 g/cm^3, but the deepest section was 1.93 g/cm^3(Carrier, 1974). Therefore, in preparation for subsequent drill testing, engineers recompacted the simulant to the densities encountered at Hadley Rille. The difficult task of achieving this high density for crushed vesicular glass and lithic particles was accomplished using electric tampers to compress each shallow layer (3-6 inches thick) as it was added to the test bed (Britton, personal communication, 1985).

CONCLUSIONS

When planning experiments for activities to take place on the Moon, investigators should remember the following.

1. Lunar soil in the laboratory does not accurately represent lunar in situ conditions. The Apollo soils have lost their original particle packing and have adsorbed volatiles.
2. Simulants can be made by ordinary means that reproduce specific properties of lunar soil such as grain size distribution, gross mineral composition, or general chemical composition.
3. Certain lunar soil characteristics are difficult to duplicate in simulants. These include agglutinates with their convoluted shapes and iron metal, implanted solar wind nuclei, impact shock effects on grains, and minerals with reduced elements.
4. A very small amount of lunar soil will be available for experimentation. Investigators should scale down their experiments and use simulant whenever possible.

Acknowledgments This paper was *substantially improved* through suggestions given *by the following* thoughtful *reviewers* D. P. Blanchard *D. S McKay W W* Mendell and *R J* Williams. Their comments are much *appreciated. This wok* was supported by contract NAS-9-15425.

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WHEAT FARMING IN A LUNAR BASE

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Green plants in a lunar base could remove CO_2 from and add 0_2 to the atmosphere, produce food, recycie most waste products, and contribute to a water purification system. We have studied wheat in the context of a bioregenerative, life-support system because of its sultability as food. its vertical leaf orientation, its excellent growth under continuous light, and available background information. Theoretical photosynthetic efficiencies suggest that yields could never exceed 195 g ^{m2} day $^{-t}$ of by matter when plants are irradiated wlth 1000 ıımo] of photons s ^-1; an irradiance that can easily be achieved with high-pressure sodium lamps. Jn practice, yields are limited by incomplete light absorption, percentage of edible biomass (harvest index), **dlgestibiiity** of blomass, and efficiency of lamps. Considering these factors, minimum figures per person might be about 6 m^2 of growing area and 3.55 kW of electrical energy. Based on ylelds currently achieved which greatly exceed the best field yields (in terms of primary biomass production), minimum figures are 24 m^2 and 13.4 kW/person. If these numbers are doubled to provide a margin of safety , a tunar farm could support 100 people in an area of about 5000 m^2. the size of an American football field Our harvest index is presently low (20-25%) because of poor seed net Future yields might be increased by manipulating temperature, humidity, nutrients, CO_2 , and the radiation emvtronment, especially if the harvest index is improved and if early canopy development is promoted. 'selecting and breeding suitable cultivars appears especially promising 'some probtems of constructing and operating a lunar farm are noted

INTRODUCTION

Growing green plants in the closed environment of a lunar base would accomplish some of the same important functions that are performed by green plants in the closed (with respect to matter) system of planet Earth. Carbon dioxide from the atmosphere is used in the photosynthetic production of organic matter, and oxygen is released as a byproduct of the reduction of water. Only relatively small amounts of water are involved in the synthesis of carbohydrate, but much larger quantities are transpired from plant leaves and other surfaces. On Earth, this evaporated water eventually condenses as rain or snow, a purification process that would also be used as part of the water purification system in a lunar base (condensation on cooled surfaces). The green plants would also be a part of the waste recycling system, utilizing mineral elements from partially or completely oxidized organic waste products. With some plants, urine could be used directly or after some dilution. Based on current technology, such an agricultural system could become a functional part of the bioregenerative life-support system in a lunar base, but future research on both biological and engineering problems is necessary to improve efficiency.

For the past four years, we have been supported by the NASA controlled-environment, life-support-system (CELSS) program. Although a variety of crop plants would be grown in a CEl.SS, we have studied wheat for the following reasons:

1. The vertical leaf orientation allows wheat to efficiently absorb high levels of solar radiation and convert this energy into a high food yield per unit area. Crop plants with horizontal leaves grow well at low light levels but generally cannot achieve such high productivities per unit area.

2. Wheat can be processed into a variety of food products that can supply a major portion of dietary carbohydrate and protein Lettuce, for example, can supply only a small portion of dietary calories before its vitamin A becomes toxic.

3. Wheat, rice, and maize are the major food crops of the world. Much is known about wheat physiology, and this knowledge can be rapidly adapted to a new environment. At the beginning of our project, much wheat expertise was already available at Utah State University.

4. Much is also known about wheat genetics, so it is possible to quickly select and breed new cultivars for a new environment.

5. Wheat forms flowers in response to long days (i.e., it is a long-day plant) and responds well to continuous light, which results in a maximum use efficiency per unit mass of the lighting system. Short-day crop plants such as rice have an obligate requirement for a dark period (about 8-12 hours, depending on species and cultivar) before they initiate seed production. Tomatoes cannot grow under continuous light, which causes their leaves to become yellow (chlorotic) and eventually die. The physiological mechanisms underlying these responses are not yet completely understood, but crop plants that are efficient food producers in a range of photoperiods are highly desirable in a CELSS.

THE COSTS *OF A* BIOREGENERATIVE *SYSTEM*

The feasibility problems for a CELSS in an orbiting spacecraft or in a lunar base are similar—although resolution of the problems seems much more straightforward with a lunar base. In either case, one must first reckon the costs, calculating what must be transported or, as in the case of the Moon, be constructed from local materials. Plants require relatively large quantities of water (which, of course, can be recycled) and relatively small quantities of mineral nutrients. In addition, they require carbon dioxide for photosynthesis. So far, in our musing about a CELSS in a spacecraft, we have tacitly assumed that the carbon dioxide would be produced by the respiration of astronauts. One can visualize a lunar base as being much larger, however, so it might well be necessary to transport carbon to the lunar base to be sure that ample CO2 would be present in the atmosphere, especially at the beginning before any recycling had occurred. Fairly sophisticated equipment is required to grow plants under completely controlled conditions, and in either case this would have to be manufactured on Earth and transported to the spacecraft or lunar base—until manufacturing capabilities at the lunar base had advanced to a relatively high level of technology. Once that has occurred, it might be possible to supply water and mineral nutrients from lunar materials. We can visualize the construction of basic growing facilities from metals and perhaps glass produced from lunar materials, but it would probably be some time before many of the necessarily advanced environmental control systems could be manufactured on the Moon.

A second consideration is the time required of astronauts or inhabitants of a lunar city to maintain the functioning agricultural system. This is an important continuing part of the cost. A third consideration is the energy requirement. Significant energy is needed to operate the farming system, and much more energy might be required to provide artificial light during the two-week lunar night.

In many ways, a CELSS on the Moon has several advantages over one in an orbiting space station. It would be much simpler to construct growth units for the lunar surface than it would be for an orbiting space station The presence of even one-sixth of the Earth's gravitational field would greatly simplify the construction or assembly of facilities and would also reduce many of the biological and engineering problems related to the growing of plants. It is still not known how well plants will respond to microgravity; some evidences suggest that plants can be grown efficiently in such an environment, but since plants on Earth normally respond to gravity (they grow upright as controlled by a delicate gravity-sensing system) in various subtle as well as obvious ways, it is not surprising that some features are abnormal when plants are grown in microgravity (Conrad, 1968). Evidence also shows that some of the symptoms plants exhibit in microgravity might also be exhibited, albeit to a lesser extent, at one-sixth g (Salisbury and Ross, 1969).

One problem presents features that are somewhat common to the spacecraft and the lunar surface The light-dark cycle differs markedly from the 24-hour cycle experienced by plants on Earth. A low-Earth-orbit space station would experience 60 minutes of sunlight and 30 minutes of darkness. This cycle could be quite deleterious to the growth and development of many plants, and we are currently investigating its effect on wheat. The 29.5-day light/dark cycle on the Moon is clearly a problem. No crop plant could remain productive after 15 days of darkness, so light would have to be provided during the dark intervals, although the light could be at irradiance levels well below sunlight

THE SIZE OF A LUNAR FARM

The immediate goal of our research effort is to determine the controlled-environment food-production efficiency of wheat per unit area, per unit time, and per unit energy input.

The Theoretical Minimum Size of a Lunar Farm

At the COz concentrations present in the Earth's atmosphere, species with C, photosynthesis (e.g., maize, sugar cane) are often more efficient than species with C, photosynthesis, which includes wheat and most crops (summary in Salisbury and Ross, 1985). At elevated CO, levels, however, C, plants are significantly more efficient than C, plants. Therefore, C_3 plants are a good choice for a CELSS or a lunar station, where CO_2 levels are expected to be elevated. From the stoichiometry of electron transport in photosynthesis and a proton requirement of three for ATP synthesis (Handgarter and Good, 1982), a theoretical minimum of 9 mol of photons are required to fix I mot of into carbohydrates. In addition, some energy is required for nitrate reduction, some is lost to fluorescence, and some is absorbed and reradiated as heat by non-photosynthetic pigments, so the best conversion efficiency that has been achieved in single leaves of higher plants is 12 mol of photons per mole of carbohydrates (Ehleringer and Pearcy, 1983; Osborne and Garrett, 1983). This is close to the conversion efficiencies achieved with algae.

With a 12-photon requirement and assuming a continuous flux of 1000 limo) s-' m' of visible radiation (about one-half full sunlight at the Earth's surface) and 10% loss for root respiration, we could theoretically produce 195 g m' d-' of dry biomass. Jf all of this biomass were edible, if the human body could metabolically obtain 4 kcal from each gram, and if 3100 kcal were consumed per person per day, then each person could be fed from the production on only 4 m'. This is the highest possible efficiency that could be achieved by any plant species.

Theoretical Energy Requirements

McCree (1972) calculates that 5 $_u$mols of photons s^produced by high-pressure sodium lamps in the photosynthetic part of the spectrum (400-700 nm) represent almost exactly one watt of energy. Thus, if high-pressure sodium lamps can be made 40% efficient at producing photosynthetic energy (efficiency of 37.6% is noted below), an input of 500 W m' could produce 1000 umol [illegible]^{2}were required per person, the energy input could be as low as 2 kW per person, using only artificial light

Potentially Achievable Size and Energy Requirements Using Higher Plants

Four factors reduce the achievable productivity of plants below theoretical: light absorption, harvest index, digestibility, and energy conversion.

I. *Light absorption.* Plant leaves never absorb all the incident radiation Our measurements suggest that, under ideal conditions, 5% of the radiation is reflected, and 1% is transmitted, even by a dense canopy with vertical leaves. It is unlikely that absorbed energy will ever exceed 95% of incident energy.

A more significant absorption problem occurs during the early stages of plant growth when small plants do not intercept all the incident irradiation. Wheat is grown at densities up to 1500 plants m^-2 (6.7 cm^2 plant^-1, 2.6 cm between plants). This is 3-6 times normal planting densities in the field, but plant leaves absorb only 50% of the irradiance when they are 14 days old and 90% when 18 days old. After day 18, light interception continues to be excellent until harvest at day 60. The germinating seeds do not require light until emergence on day 3, but absorption efficiency is low from day 3 to about day 18. In our current system, this loss is about 20% of the total area and energy required to grow the crop. A mechanical system to alter plant spacing during early growth (so plants are moved apart as they mature) could eliminate some of this loss. Such systems are being used in commercial controlled-environment food production.

2. Harvest Index The most significant limitation to food production is that not all the biomass produced by the plants is edible. The edible divided by total biomass (both dry) is called the harvest index A lettuce crop has about 80% edible leaves and 20% inedible stem and roots. Potatoes can have a harvest index of edible tubers of 80% of

the total biomass, and wheat can reach 60% edible grain on a dry-mass basis. Under the best conditions, there is a 20-40% loss from inedible plant materials. These could be consumed by animals (chickens, pigs, rabbits, *etc.*) to produce edible protein for humans, although this would introduce some complications.

Many authors have suggested crops with edible roots, leaves, and reproductive structures; sweet potatoes and sugar beets are examples. In most cases, however, only the young leaves are edible, although it is the mature tubers, roots, fruits, or seeds of such plants that are normally harvested. Unusual food crops should be considered for a CELSS, but claims of high productivity and high harvest index often cannot be substantiated

3. Digestible *energy per* unit *edible* biomass When the energy content of oven dry wheat is determined by combustion in a bomb calorimeter, values as high as **3.94** kcal per gram are obtained, but the digestible energy is only about 3.7 kcal This relationship also holds for other food commodities.

4. Energy conversion. High-pressure sodium lamps produce 376 W of energy between 400 and 700 nm per 1000 W input power. This makes them 37.6% efficient (Chris Mpelkas•, personal communication, 1985). Their output, however, must be reflected down onto the plants. The best reflectors are about 90% efficient This makes the overall efficiency of the system 33.8%. Efficiencies of 26% have been achieved on a commercial scale. The Phytofarm in Dekalb, Illinois, has an energy input of 304 W m^{-2} from high-pressure sodium lamps and a photon output of 400 umol s^{-1} photosynthetic irradiance (Maynard Bates, personal communication, 1984).

Considering these four factors, the potential size and energy requirements that can be achieved in a lunar farm can be calculated as follows:

Theoretical (with 1000 umol s^{-1} m^{-2} input)	
90% light absorption *over* life *cycle*	175 g m^{-2} d^{-1}
80% harvest index	140 g m^{-2} d^{-1}
Multiplied by 3.7 kcal g^{-1} (92.5% digestible)	518 kcal m^{-2} d^{-1}
Assume 3000 kcal per person per day	
3000 kcal $person^{-1}$ d^{-1} divided by 518 kcal m^{-2} d^{-1} = 5.79 m^2 $person^{-1}$	
Round to:	6 m^2 $person^{-1}$
Energy requirement	
1000 umol s^{-1} m^{-2} =	*200* W m^{-2}
200 W m^{-2} divided by 0.338 efficiency =	592 W m^{-2}
592 W m^{-2} × *6* m^2 *= 3552 W* $person^{-1}$	*3.55* kW $person^{-1}$

These theoretical efficiencies would be very difficult to achieve with a crop plant (such as strawberries) that is chosen for its aesthetic qualities and flavor rather than

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•at Sylvania Test and Measurements laboratory, Danvers, MA for its productivity. Nonetheless, research will need to be done on all species grown in a CELSS to optimize their edible productivity.

Currently Achievable Productivitles with Wheat

During the past year, after spending much time on designing and building research chambers to create optimum environmental conditions for studies on wheat productivity, reproducible production data have been obtained that can be used to estimate the size of a lunar farm that could be built today. So far, we have been highly successful in converting photosynthetic irradiance into biomass but much less successful in converting total biomass into edible yield

We measure short-term rates of carbon fixation in wheat canopies with a gas exchange system that includes a pressurized growth chamber (Salisbury, 1984). A canopy of 0.8 m' is grown in this chamber with the roots in a sealed, recirculating, hydroponic system (roots fed with nutrient solutions). A light input of 1000 umol s' m' in an atmosphere enriched to 1700 ppm CO' has resulted in photosynthetic rates as high as 58 μmol s̄' m' of carbon dioxide absorbed by the leaves. If we subtract for root respiration and multiply by the photoperiod each day, this figure can be converted into a daily growth rate. Root biomass in our hydroponic systems is typically only 10% of the total (20-30% in the field). Subtracting this estimated 10% respiratory loss and assuming continuous light, this photosynthetic rate should result in a growth rate of 135 g This compares well with the theoretically achievable growth rate noted above of 175 g m^-2 d-^-1 (at 90% light absorption).

We measure actual growth rates at weekly intervals by removing a 02 m' section of plants (about 200 plants in a rigid support), blotting the roots dry, weighing the section, and returning it to the hydroponic solution A few plants are destructively harvested and dried to determine percent dry-mass, from which dry-mass growth rates can be calculated. We have measured growth rates of 875 g m^-2 week^-1 or 125 g m^-2 d^-1. This growth rate is close enough to that predicted from the gas exchange measurements to serve as a validation of the short-term photosynthesis measurements, Unfortunately, it takes about 22 days for a group of plants to reach this growth rate, and the rate gradually decreases as the plants mature. These factors combine to make an average growth rate of 90 g m' d-' over a 60-day life cycle.

The production of 90 g m' d' total biomass is truly remarkable by conventional agricultural standards. 'typical field productivities are less than 10 g m' d-', and 20 g m' d-' is exceptional. Wheat is obviously stressed even in the best field conditions. The stress factors could be low carbon dioxide and/or low light, neither of which would be economical to change in the field

These high growth rates are the good news. The bad news is that we have not yet been able to cause wheat growing at high rates to partition a normal percentage (40 to 50%) of its total biomass into edible grain. A crop producing 90 g m ^{2} d'1 should have a grain yield of 35 to 45 g m' d''; our crops have produced only 20 to 25 g m' d''. We expect to solve this problem, but at the moment, the reasons for this low harvest index remain unclear. A comparison of our yield components with field production data offers some clues (Table 1).

Table I. A Comparison of Controlled Environment and Field Productivities

	life cycle (days)	Seed yield (g m^2)	Harvest Index	Heads per m^2	'seeds per head	Mass per seed (
Controlled environment	60	1300	25%	3000	15	29
High yleld from &Id	100	800	45%	800	30	33

Continuous light and a constant high temperature (27°C) are principal factors responsible for shortening the life cycle from 100 to 60 days. These same two factors may also be partly responsible for the low seed number per head, which is associated with our low harvest index. Low seed number per head is the result of few spikelets formed on the head (spike) during the floral induction phase (days 15-22) and/or poor seed set during and following the pollination period (called *anthesis* days 30-37). There is published evidence that the shortening of the growth period associated with long photoperiods results in the production of fewer spikelets per spike during floral induction (Rawson, 1970; Lucas, 1972).

The main problem appears to be poor seed set in existing florets. Wheat is self-pollinated, and the anthers (male flower parts) do not appear to shed pollen normally in our conditions. This inhibits fertilization and thus seed set We are just beginning to study the problem.

Our reproducible seed yields of 20-25 g m-' d-' give a harvest index of about 20%, and it is reasonable to expect that, based on a better understanding of floral initiation and pollination, we can double this to about 40% (40-50 g m' d-') without any additional energy inputs.

With a harvest index of 40% (instead of 80%) the above size and energy figures for the lunar farm must be doubled: 12 m' and **6.68** kW person'. With a harvest index of 20%, the figures are multiplied by four: 24 m' and 13.4 kW person'. Even if these figures were doubled again to provide a large margin of safety plus room for working aisles between groups of plants and for other work areas, they would not be discouraging from the standpoint of a lunar base. A medium-sized classroom has on the order of 50 m', and 100 humans could be supported by a lunar farm of 5000 m' at most Based on the most optimistic figures given in the above sections, this could be reduced to about 600 m'. (A standard American football field, including end zones, has an area of **5364** m^2.) We estimate that the lunar farm designed to feed 100 people might be operated by a staff of 2-10 lunar farmers.

This is not to suggest that a lunar farm would be inexpensive and easy to construct. It might have to consist of relatively small, self-contained modules, all initially brought from Earth. If sunlight were used directly, the farm would need a transparent or translucent covering strong enough to withstand internal atmospheric pressure (probably reduced from that on Earth), and, more importantly, micrometeorite bombardment The initial quantities of equipment, water, carbon dioxide, and minerals that had to be brought from

Earth would be formidable—but quantities of food required to support 100 inhabitants of a lunar city would provide an even more formidable continuing transport problem.

The energy required to operate such a farm completely with artificial light from high-pressure sodium lamps would also be very large (334-1340 kW, based on the above figures). If solar cells are used to collect energy, it must be realized that only about 5% of sunlight will eventually be converted to light from the lamps, assuming highly efficient solar cells and lamps. With these ideas in mind, it is important to consider direct use of sunlight during the lunar day. The slowly changing position of the Sun in the lunar sky might be a problem, but that could probably be solved with reflectors, translucent and diffusing glass, or even bundles of fiber optics. It is claimed that fiber optics can transmit as much as 50-68% of the light, but even if light is first greatly concentrated by fresnel lenses, the size of the required bundles of fiber optics to irradiate a lunar farm is a bit staggering. If the lunar station is powered by a fairly large nuclear plant, as is often proposed, power for irradiating the plants might not be a serious problem It is important, however, for engineers to be aware of the high light levels required by plants for optimum yields Adequate illumination for an office environment is clearly not sufficient light for growtng plants in a lunar farm.

INCREASING THE YIELDS

We calculated above that a theoretical maximum production of dry matter when 90% of 1000 umol s^{-1} m^{-2} of light was absorbed was about 175 g m^{-2} d^{-1}'. Our figure of 90 g m-' d-' represents an efficiency of about 51%. The challenge is to close the gap between 51 and 100%. There are many parameters to manipulate. Consider a few.

Temperature. So far we have not really studied temperature. We use values (27°C) reported to be optimal for wheat with CO_2enrichment Higher temperatures could shorten the life cycle but might decrease yleld per day. With a few plants, varying temperature on a 24-hour cycle increases yield, but this does not seem likely for wheat There could be surprises.

Humidity. There are two possible adverse effects if humidity is too high First, because transpiration is reduced under such conditions, leaf cooling is less, and leaf temperatures may increase above optimal levels when irradiation is as high as it is in our chambers. Second, because transpiration is reduced, mineral uptake may be reduced. Evidence from recent experiments in our laboratory suggest that this is an important effect when CO, levels are elevated, which causes partial stomatal closure. (Stomates are the pores on a leaf surface through which water evaporates and CO_2 enters.) It is easier for us to maintain optimal nutrient conditions within plant tissue when humidities are lowered This does not appear to be the case when plants are growing under less ideal conditions.

Nutrients Plants are grown with their roots in aerated, circulated, nutrient solutions We find that mineral nutrient concentrations in these solutions can be very critical, and responses to nutrients can change as other parameters change—as just noted for humidity. We have expended much time developing adequate nutrient solutions and techniques to provide them, but we have not yet solved all the problems. Our youngest plants sometimes show deficiency symptoms that disappear as the plants mature (i.e., when they reach about two weeks of age). Iron, manganese, phosphate, and other nutrients can be problems, especially as the pH increases rapidly as nutrients are absorbed. We have been able to control pH within fairly narrow limits by providing a balance of ammonium and nitrate ions and by using an automated system to add acid when needed. Ammonium ions are exchanged for hydrogen ions produced in the plant roots, decreasing pH, and nitrate ions are exchanged for bicarbonate ions from the roots.

Carbon dioxide concentration. CO, is typically limiting at ambient levels (320 ppm = IS mmol m^-3 at sea level). Yields are greatly increased when CO, levels are raised around the plant leaves. We elevate to 1700 ppm (60 mmol m^{-3} at our elevation). Stomates tend to close completely when CO, levels are elevated too high, but we are not yet sure of the upper limits. It would be possible to manipulate other gases, and lowering oxygen levels would also increase rates of photosynthesis, probably without stomatal closure. So far we have not invested the time and money required for such a study.

The radiation environment. There are several aspects of the light environment that must be studied:

1. Light level (irradiance)—Increasing irradiance would not help in the above example to raise efficiency; indeed, it might lower the efficiency of photosynthesis if the process had already reached light saturation. If saturation had not been achieved, however, an increase in light level might raise absolute yields expressed as g ^{ma} d$^{-'}$. With today's technology, it is difficult to get and expensive to maintain light levels much above the 1000 µmol s$^{-'}$ m$^{-'}$ that we have used, although we have now outfitted one growth chamber so that we obtain 2000 umol s$^{-'}$ m', equivalent to sunlight at noon Preliminary results show that photosynthesis increases considerably compared with half of sunlight, but photosynthesis was not quite doubled.

2. tight quality (spectrum)—The balance of wavelengths can be modified in an almost infinite variety of ways, so there is much room for experimentation. One of these approaches has been taken with rather interesting results. Healthy wheat plants have been grown that produce normal grain under low-pressure sodium lamps. The energy from these lamps is nearly all confined to one line in the spectrum at 589 nm. The lamps are efficient at producing light energy, so they might be of use in the lunar farm during lunar night. Furthermore, it was found (Guerra *et a1.,* 1985) that secondary metabolites (specifically lignin) are more dilute in tissues, and activities of two key enzymes (PAL and TAL) in the synthesis of secondary metabolites are greatly reduced in plants grown under these lamps. This could mean that primary metabolites (starch, protein, fat) could be higher in the plants, although this has not yet been shown to be true.

In general, light quality has many important photomorphogenetic effects. For example, light quality might influence the partitioning of assimilates in such a way that harvest index is increased.

3. Light cycling—Daylength (photoperiod) has profound effects on many plant responses including flowering, seed filling, tillering (formation of axillary stems in grass plants), and dormancy. Hence, photoperiod can and does influence the duration of the life cycle as well as the harvest index We are manipulating the photoperiod to see if we can increase seed set

4. Canopy development—Our results so far show that canopy development and harvest index are probably the most important factors limiting our grain yields. The above calculation assumes that 90% of the incoming radiation is absorbed, but this is far from true when the plants are small. The leaf-area index ([Al) expresses the number of layers of leaf tissue through which a given ray of light must pass (on average) before it strikes the substrate. For maximum absorbance of incoming radiation, a high LAI is essential. Wheat reaches an LAI of 6-8 in the field and has reached 14 in our controlled conditions, At that point, light at the bottom of the canopy is only about 10-20 umol m^{-2} s-'. Absorption is extremely high, and photosynthesis reaches about 77% of the theoretical maximum. This suggests that we cannot improve photosynthetic efficiency more than perhaps 10-20% by manipulating parameters as suggested above—although it remains worthwhile to attempt to do so.

THE MOST PROMISING FUTURE WORK

Yield per unit area per unit time is much more than photosynthetic efficiency of a mature canopy. There are two especially important characteristics of a wheat farm that strongly influence yield and can still be manipulated: the time to canopy closure and the harvest index Both can be influenced by manipulation of the environment and of the plant's genetics.

As noted, plants may be moved apart as they mature, but such techniques could be more trouble than they are worth. It is also possible that environmental manipulations could produce a leafy plant quicker, and/or at a savings of energy input Since wheat is a facultative long-day plant, plants could be started under short days, perhaps with somewhat reduced irradiance levels, This would save electrical energy if it were done during the 14-day lunar night, and the retarded flowering might allow the development of a more leafy plant before its energy resources were directed toward flower production and seed filling.

Cultivars are being selected with a high genetic potential for rapid canopy closure. (Two members of our team, Rulon Albrechisen and Wade Dewey, are wheat breeders.) Particularly promising for rapid canopy closure are uniculm cultivars that produce only one or a few tillers per plant Normal wheat plants close the canopy by sending out as many as 3-15 tillers, each of which produces a head of wheat This takes time, and plants cannot be too closely spaced at the beginning or they become overcrowded in the field. A cultivar that produced only one to a few tillers could be planted in a dense pattern to begin with, so that the canopy was rapidly closed. Five segregating generations, incorporating some desirable agronomic characteristics into a uniculm cultivar have been completed. We have also selected six generations of dwarf wheat (35 cm tall) under CO_2-enriched continuous-light environments. In essence, a special wheat plant for a CELSS is being designed.

There is certainly much potential for increasing yields by increasing harvest index (by producing more wheat seeds per plant). Again, the most promising approaches are to manipulate environmental factors and to select suitable cultivars. As noted, there is good reason to believe that manipulation of photoperiod will increase seed set We have now tested about 600 cultivars and find great differences in their growth, yield of grain, and harvest index. Harvest index is usually highest in dwarf (30 cm) cultivars, but so far their overall yields are relatively low.

SOME CONCLUSIONS

It should be quite feasible and probably profitable (depending on the permanence of the lunar base) to establish a wheat farm on the Moon. There are serious problems (eg., the long lunar night), but solutions are presently available, and future research could provide even better solutions. Based upon current data, it appears that about 6-25 m^0 should be sufficient to provide food for an active adult A lunar farmer would not be at the mercies of unpredictable weather, as earthly farmers are; rather, he or she would be at the mercies of the inherent tendencies for mechanical equipment to falter and of his or her own propensities to make human errors. This being the case, an inhabitant of a lunar city might feel more at ease if there is ample area of a lunar farm dedicated to producing food for his or her survival.

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ENVIRONMENTAL CONSIDERATIONS AND WASTE PLANNING ON THE LUNAR SURFACE

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Lunar operations in the near future will pose waste management judgments. Final decisions must be established to maintain a high degree of operational efficiency within technological and economical limits. The purpose of this study is to identify environmental considerations arising from a lunar manufacnaing facility. Certain assumptions guide the setup and operation of the lunar base presented. The author does not suggest that such assumptions will become reality but, instead presents an outline of a base that appears promising at the present time. The goal of this paper is to promote conversation and thought towards fundamental decisions that will need to be made before the building of lunar facilities begins. The following assumptions were taken (I) the base will be manned by a crew of 15 workers (2) the primary function of the base will be the extraction of oxygen from ilmenite ($FeTiO_3$) via a hydrogen reduction process; (3) nuclear power will form the central power supply on the surface; (4) a semi-closed life support system will be employed with the total resupply of food coming from Earth.

Many questions still exist as to what will be done with much of the refuse brought about by man's existence on the lunar surface. What will become of spent nuclear reactors? Will carbon and phosphate salts from man's waste be stored for later use? Will chemical transportation create a significant lunar atmosphere? These are some of the myriad of questions that confront planners of the lunar base. In order to achieve the best possible results from the operation, questions like these will soon have to be addressed.

INTRODUCTION

If NASA's tentative schedule is to be kept and the lunar facility is to be implemented before 2010, it is not too soon to begin contemplating the impact of man and his activities on the lunar surface and to discuss ways in which his presence and activities will not limit his possibilities in more distant times. A principal goal of any project such as the proposed lunar facility is to grant the most alternatives, economically and technically feasible at the time, to future planners. The paper identifies several wastes that promulgate future operational choices and several that limit more distant activities.

Table 1 presents a rough estimate of the oxygen needs that NASA might typically require at the time oxygen production begins on the lunar surface (oxygen needs and trip parameters were developed through personal communication with B. Roberts and W. Richards of the Johnson Space Center, 1984). A typical lunar oxygen mission can return a net amount of liquid oxygen (LOX) to low Earth orbit (LEO) totaling 54,400 kg (assuming an aerobrake weight that is 14.5% of entry weight, an overall trip I. of 480 s, and an OTV and lunar lander oxygen to fuel ratio of 7:1; mass payback ratio

Table 1. Typical Oxygen Needs of NA'sA in LEO as Lunar Facility Becomes Operational (Yearly)

Mission Rom LEO	LOX per Mission (kg)	Total Missions	Total LOX (kg)
Lunar	77,200	4	309,000
Manned Geosynchronous	38,000	4	152,000
Other		—	91,000
		Total	552,000

is 2.6). The production rate on the surface to get this amount of LOX to LEO is approximately 200,000 kg. The other 146,000 kg of LOX is used in the transport of cargo to LEO. This brings the lunar oxygen production rate to 200,000/54,400 or 3.7 kg LOX produced on the lunar surface per kg LOX free in LEO.

Referring to Table 1, a total of 552,000 kg LOX will be needed in LEO. Therefore the lunar oxygen production rate is set at 3.7 , by 552,000, or 2.1 x $10^{\wedge 6}$ kg LOX per year.

MINING, BENEFICIATION, AND THE HYDROGEN REDUCTION OF ILMENITE

The reduction of ilmenite with hydrogen holds much promise for the production of oxygen on the lunar surface for several reasons. (1) The process employs only one significant chemical equation, $FeTiO_3$ + H_0 — Fe +TiO_2+ H2O. The water vapor is electrolyzed back to hydrogen, to be recycled, and oxygen. (2) The lunar maria is known to be 10% or more, by weight, ilmenite. (3) Beneficiation, with an electrostatic separator, is relatively easy and yields material of high purity for further processing.

Beginning with the production rate of 2.1 x 10^{6} kg LOX and working under the assumptions of (a) 90-100% conversion in the reaction above, (b) lunar soil consisting of 10-12% ilmenite, (c) soil density of 1,800 kg/m3, and (d) no significant loss in the beneficiation process, the following approximate values are arrived at 20,000 tons mined/year, 1.1 X $10^{\wedge 5}$ m' bulk soil mined/year, and 18,000 tons $FeTiO_2$ generated/year.

LIFE SUPPORT

It is possible that the permanently manned outposts in space, at least initially, will have a life support system that is semi-closed (Spurlock and Modell, 1979). To achieve a greater payback from the lunar operation, components of water and air must be recycled to limit resupply transportation costs. The initial facility, however, may not be capable of supplying its own foodstuffs. The total resupply of food from Earth is therefore assumed.

Table 2. Basic Requirements and *Waste* Generation *for a* Lunar Crew of 15•

Requirements	Per Man, Daily (kg)	Total for Crew (kg)
Metabolic oxygen	0.9	13.5
Drinking water	3.6	54.0
Hygiene water	5.4	81.0
Food	0.6	9.0
Waste Production		
Carbon dioxide	1.0	15.0
Water vapor	2.5	374
Urine	1.5	22.5
Feces	0.16	2.4
Metabolic heat	12,660 kJ	189,900 kJ

·'sharpe (1969), p. 107.

Table 2 lists the material that a life support system must be capable of handling. Figure 1 displays the various units in a feasible life support system.

Central to the support system is the oxidation water reclamation unit For many years, Robert Jagow has studied the wet oxidation process of waste recycle as it exists in industry and in its application to various other environments (Jagow, 1972, 1975). From this process, Jagow has shown that wash water, human waste, and trash can be oxidized at elevated temperatures and pressures to produce water, carbon dioxide, and a cake of phosphates and sodium salts. The water may be recycled for direct human use, and the carbon dioxide could be converted to oxygen and carbon. From Table 2, the carbon dioxide from respiration from the 15-member crew will be about 15.0 kg/day. About 1500 kg of pure carbon will be produced yearly.

POWER

A dependable, constantly operative power supply will be needed on the lunar surface. Survival will be dependent upon a few kilowatts of power to clean the air of the workers, regenerate the oxygen, and recycle the water. At the same time, large amounts of energy must be produced to accommodate the taxes imposed by the processing facilities. Nuclear power holds a promising key to these lunar needs.

Nuclear power is attractive for several reasons. Proposed units are easy to maintain and operate. It is anticipated that the unit can be dropped into place, started, and left alone until its productive life is over. Nuclear power units have a high energy density. Nuclear power is also capable of producing large amounts of both thermal and electrical energy—five to twenty watts thermal to every one watt electrically produced (French, personal communication, 1984).

Nuclear power units now in study under the program name SP-100 are being adapted to the zero-g environment These reactors will have a lifetime of seven to ten years

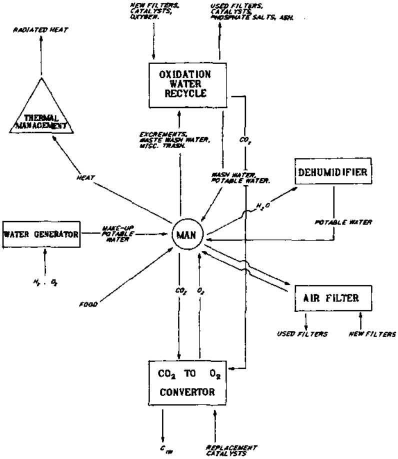

Figure 1. *A feasible semi-closed life support* system.

and will be capable of generating between 100 to 400 kW of electrical power. It has been proposed to conform such units to the lunar environment, employing native soil for shielding purposes (French, 1984).

TRANSPORTATION

Transport of man and materials to low lunar orbit (LLO) will conveniently be adapted from geosynchronous transport now being drawn up by NASA. Heavy lift vehicles (HLV) and the space shuttle will bring material to LEO, and orbital transfer vehicles (OTV) will travel to LLO, transferring the payload to lunar descent vehicles.

Initially it is conceivable that the lunar descent vehicles will be disposable. Until the production of oxygen begins, there will be no need to bring substantial material off the surface and, further, no ability to fuel vehicles after descent Upon the production of oxygen, however, a great desire will arise to make these lunar surface transports reusable. Many flights will be needed to transport oxygen off the lunar surface for the trip back to LEO. If such flights were made with disposable transportation, operation costs would reduce the operation's payback

NASA has estimated the total base mass to be approximately 181,500 kg at the time of oxygen production. Lunar descent platforms, each having a mass of 4,900 kg, have been estimated to be capable of transporting approximately 18,800 kg of cargo (Richards, personal communication, 1984). Thus, to transport the initial base to the Moon, 181,500/18,800 or about ten trips need to be made. This leaves 10 x 4,900 kg or 49,000 kg of scrap material on the lunar surface.

POTENTIALS AND PROBLEMS

Discussion of potentials to increase future operational alternatives and identification of problems that may arise from man's existence on the Moon can proceed from the general outline of the major components of the lunar base given above.

If man is to become self-sufficient on the lunar surface, the groundwork must be laid to close his life support system. Man must eventually develop food production on the lunar surface and cut the "umbilical cord" that will tie him to Mother Earth.

Current work, under the program name Controlled Ecological Life Support System (CELSS), is proceeding to achieve this goal. An experimental bio-regenerative life support system is being considered for attachment to the Space Station in 1998. It is possible that a similar system could be landed on the lunar surface. In this event, advantages exist to aid in the success of this project and reduce the economical cost incurred.

As discussed above, the life support system generates carbon from the conversion of carbon dioxide to oxygen and filters phosphate salts from the water reclamation unit. This material need not be deemed waste, since such rare and life-required elements could be employed in a pilot agricultural facility. It seems logical that these elements from the support system should be stored for later use. It has also been proposed that parts of the discarded transport platforms (up to 40%) be made of similar rare lunar materials (Babb *et al.,* 1984). In this manner, what might previously be considered waste could be used to the advantage of man

Nuclear power units have potential additional use. This opportunity arises from the large quantity of thermal energy that reactors generate. This excess heat can be radiated into space, if desired, and be considered waste. If, however, processing facilities such as the hydrogen reduction process are developed in a way as to be receptive to this alternative energy source, waste can again be used to the advantage of the base.

Several waste problems still remain unanswered. Will those operating the lunar base consider it economically feasible to refill the mining pits previously excavated? Many now working on this subject seem to believe that the idea of a moral duty to leave the Moon as it has been for eons is sheer "lunacy." However, Williams et al. (1979, p. 283) stated, "Although conveniently located craters can be refilled with wastes initially, back filling the mine site is the only feasible long term solution" Backfilling here would include the ilmenite-poor soil (90% of that is mined) and the reduced ilmenite, $FeTiO_2$, from the reactor.

What will become of the spent nuclear reactors? If those under design in the 8E-100 program are to be employed, the energy rating of 100 kW and the high demands of the lunar facility will necessitate several reactors. To reduce the cost of transport, it has been proposed to strip the reactor of its shielding and, in its stead, employ native soil. This requires that the surrounding area be off-limits to personnel and overhead flights (French, 1984). The reactors will provide their services for about ten years, at which point they will be shut down Two options exist at that time. One choice is to dig up the reactors and refuel them or move them to a different locality. This procedure, however, will require a strong surface infrastructure capable of safely handling such a technically difficult task; perhaps not developed fully enough for several decades after the initial setup. The second option is then forced upon the lunar base—to leave the reactors buried Since the prospect of tens of discarded nuclear reactors will face the lunar facilities after several years of operation, the need of strict reactor management will arise to avoid limiting future operational plans. If not, the prospect of scattered sites, each being off-limits to lunar activities, will confront more distant lunar worker&.

Will chemical transportation cause an impact in the formation of a restrictive lunar atmosphere? It has long been realized that the farside of the Moon provides astronomers the perfect locality for an observation post; the existence of a distinct lunar atmosphere will limit the options of these astronomers. It has been estimated that a long-lived atmosphere (with a life of several hundred years) could be created on the Moon with a mass of 10^{8} kg or equivalently if an amount on the order of 60-100 kg/s entered for an extended period of time (Vondrak, 1974).

Calculations can be made for the scenario presented here. For each lunar descent and ascent a total of 98,000 kg exhaust vapor is formed (Richards, personal communication, 1984). Since each trip to the lunar surface returns 54,400 kg LOX to LEO, and a total of 552,000 kg of LOX is to be returned to LEO, about I I trips must be made in the course of a year. In one year, then, I I by 98,000 kg or I x 10^{6} kg of vapor enter the lunar atmosphere. This is on the order of 0.01 kg/s.

One may conclude that although a long-lived atmosphere will not be developed in this case, a finite cover can be formed and may pose astronomical limitations. Further, if oxygen requirements increase in time and more flights on and off of the lunar surface occur, while some alternative form of transportation (e.g., a mass driver) is not employed, the formation of a substantial lunar atmosphere is not out of the question.

What are the legal responsibilities of NASA and the United States when constructing and operating the base? In 1967, President Lyndon Johnson ratified the ""meaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies," and pledged to abide by certain guidelines in outer space. The following passages are from this treaty.

> *Art 1, para.*
>
> "The exploration and use of outer space, including the moon... shall be carried out for the benefit and in the interest of all countries, irrespective of their degree of economic or scientific development and shall be the province of all mankind°
>
> *Art DC para. I*
>
> State parties to the treaty.... shall conduct all their activities in outer space including the moon... with due regard to the corresponding interest of all other State Parties to the treaty. State

> Parties shall pursue the studies of outer space, including the moon... and conduct exploration of them so as to avoid their harmful contamination.
>
> A State Party to the treaty which has mason to believe an activity or experiment planned by another state parry in outer space including the moon.... would cause potentially harmful interference ploration and use of outer space.. . may request consultation concerning the activity or experiment'

If NASA intends to operate processing facilities on the lunar surface, it must not alter the existing environment If this is not done, it will surely elicit a response from other signatory nations. Intentions of operations and their impact must, in accordance with the treaty, be available to these nations. Therefore, NASAS lunar facilities must not cause other State Parties to question the environmental impact of base activites.

Many prospective lunar activities at this time have unanswered questions and pose many waste management problems. These problems arise from units and procedures that appear at this point promising to be included at the initial lunar base. The opportunity exists for several of the wastes to be utilized by the crew to increase opportunities and decrease cost of operation in the lunar environment. Table 3 summarizes the environmental considerations identified by this study. Questions and opportunities that are open to base planners must be addressed soon to deal with these waste problems and provide the maximum future operational options. It is not too soon to begin to address the impact of man and his activities on the lunar surface.

Table 3. 'summary of Environmental Considerations Arising from Proposed Lunar Operations and Facitities

Waste origin	Environmental Consideration	Potential Benefit
Transportation Hardware	Use of disposable descent platforms for pre-oxygen production transportation places hundreds of tons of scrap material scattered in the base vicinity.	Building platfom. of matertals beneficial to man on the Moon allows him to accumulate lunar deficient elements.
Chemical Propulsion	Traditional chemical transportation used at projected levels could lead to experimental and operational limitations.	None.
Life Support 'system (155) material	Man's life processes produce bin-wastes. Most is recycled however initial LSS is not closed, giving rise to phosphate and carbon residue.	life support residue is rare to the Moon These materials can be utilized at a later time for lunar agriculture.
Nuclear Power	Reactors stripped of man-made shielding must employ native soil to limit radiation Surrounding area will be restricted to personnel	Thermal energy produced by reactors can be used in material processing.
Mining and Processing	'strip mining of topsoil produces large pits and piles on the surface. Unprocessed materlal is rejected by processing facilities.	None.

Acknowledgments. This presentation was made possible by Worcester Polytechnic Institute, being adapted from a project under the guidance of Dr. Albert 'sacco, Chemical Engineering.

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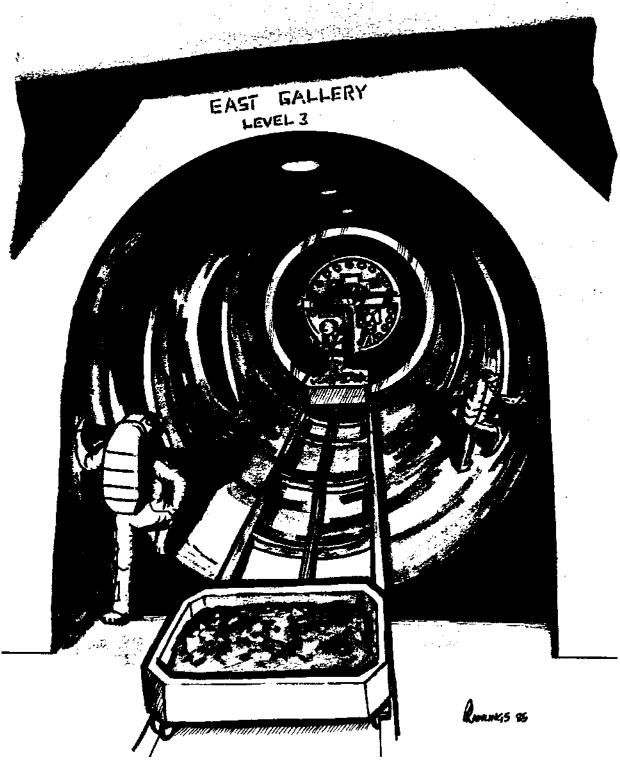
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FRACTIONAL DISTILLATION IN A LUNAR ENVIRONMENT

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The establishment of a permanent lunar base will undoubtedly employ distillation operations as a routine practice. Reclamation of vital fluids along with products from chemical processes will lend itsetf to fractlonal distillation The lunar environment, with reduced gravity and pressure, will dictate design modifications and offer some pleasant advantages. Column area will increase to maintain the same ftow rates as Earth-based counterparts Plate efficiencies can increase, allowing shorter columns Thermal insulation will be facilitated by the lunar atmosphere, as well as low pressure "vacuum" distillatlon.

INTRODUCTION

With the development of a reliable space transport system, extraterrestrial engineering is becoming a respectable field of endeavor. The detailed engineering for maintaining a space station or lunar base, along with possible manufacturing processes, presents a challenge for scientists and engineers.

The establishment of a permanent lunar base will employ separation techniques as part of routine necessity. Recycling precious body fluids, in addition to solvents and products of chemical manufacture, could lend itself to fractional distillation. The lunar environment, with reduced gravity and pressure, will offer some unique possibilities for clever designs with a concurrent struggle to overcome the hardships.

Why use an age-old process like distillation when there are many "space age" separation techniques (such as membrane technology)? Distillation uses simple, hearty equipment that operates in a dependable manner, equipment that is not easily damaged if operation is in error. Many of the construction materials could ultimately be derived from lunar sources, saving the transportation costs of Earth-based goods. Most important, distillation uses heat energy as the main driving force for separation.

On the Moon, shaft and electrical energy will be at a premium. Whether from solar, combustion, or nuclear sources, heat energy will be more abundant and more efficiently obtained than shaft or electrical energy. In the allocation of such a valuable commodity, it makes good sense to employ processes that utilize heat directly, saving the shaft and electrical energy for those processes that cannot be driven any other way. Waste heat from ongoing processes may be of a quality suitable for driving distillation, thus realizing further economy.

The lunar environment will offer some unique advantages for distillation processes. Vacuum distillation will be possible due to the cryogenic temperatures available on the Moon. With vacuum distillation lower heat loads are realized with cleaner separations and with the possiblity of breaking azeotrope systems. With a radiation barrier the distillation columns will be essentially enclosed in a giant "thermos bottle," realizing very low heat losses, so the energy injected into the processes will be used efficiently for driving the separation. The constant nature of the lunar atmosphere will facilitate the process control, resulting in consistent product output and quality. In contrast, heat loss from earth-based columns is of major concern, especially coupled with changing weather patterns that complicate the process control.

Fractional distillation is a mature engineering field backed with years of experimentation that resulted in practical design. The approach taken here is to utilize this existing knowledge, coupled with dimensional analysis and scaling arguments, to modify the design of Earth-based columns for lunar operation

BACKGROUND IN DISTILLATION EQUIPMENT

The anatomy of a fractional distillation process is shown in Fig. 1. The heart of the unit consists of the fractionating column, basically a tall vertical pipe where the liquid and vapor experience intimate contact and where mass transfer between phases is effective, thus achieving component separation. At the bottom of the column is the reboiler, a vat of boiling liquid from which the vapors flow upward into the bottom of the column while the condensed liquid emanating from the column flows downward into the reboiler. The heat for driving the separation is injected into the reboiler.

At the top of the column is an overhead condenser that converts the enriched vapor effluent into a liquid, rejecting heat into the environment A portion of this liquid is tapped off as head product, the balance being returned to the top of the column as reflux The ratio of the amount of liquid returned to the amount tapped off is called the reflux ratio and is an important quantity in the design of a distillation process.

Most distillation processes are designed to operate on a continuous basis, unlike the familiar connotations of a moonshiner's batch still for making "white lightning." A continuous feed is introduced into the column at the point where the concentration of components in the feed matches that in the column. The enriched head product is continuously withdrawn from the top while depleted bottoms are continuously removed from the reboiler.

The design of what goes inside the column to achieve the intimate contact between vapor and liquid is somewhat of an art as well as a science. The column can be filled with plates, each having a standing pool of liquid that vapors bubble through, giving discrete or stage-wise contact The column can be packed with irregular objects, providing continuous contact between the liquid trickling down and vapor percolating up. Presently, the most popular column design uses plates, with future trends leaning towards packed columns. This paper will deal with plate-type columns, with packed columns being the subject of another study.

There are many types of plate designs, with sieve tray plates being the most common. The sieve tray plate will be considered hem initially, with the scaling arguments derived being general for most types of plate columns. Figure 2a shows a cross section of a

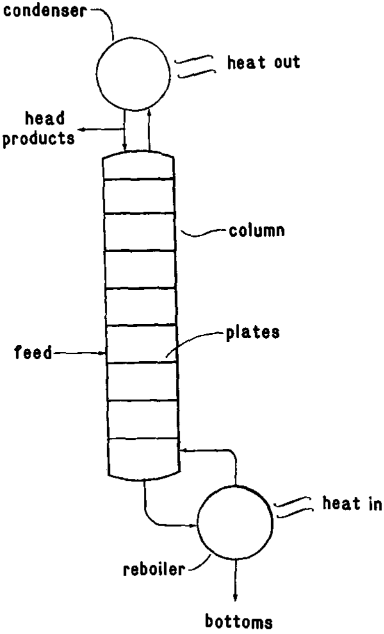

Figure. I. Schematic *of a basic fractional* distillation *process*

portion of a column containing a sieve tray plate, while Fig. 2b shows the top view. A pool of liquid, usually 10-20 cm deep, stands on top of a perforated plate with holes ranging from 4-15 mm in diameter. The liquid is kept from weeping through the holes by a steady stream of vapor pushing upward, emanating from the liquid on the plate immediately below. The vapor, with intimate contact, bubbles through the pool of liquid and thereby condenses. The heat released upon condensing vaporizes a corresponding amount of liquid, which pushes upwards as vapor to bubble through the next higher

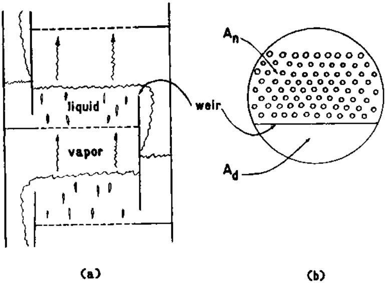

Figure 2. (a) *Cross section of* a *column with sieve tray plater (b) top view of a sieve tray plate.*

plate. Insulation is critical in the operation, because the energy for vaporizing the liquid on a plate comes from the condensing vapors; any heat loss hinders this interplay.

The liquid level is maintained by a lip or weir, over which the liquid can splash and flow down a passage called a downer to the next lower plate. A liquid seal is provided so the vapors cannot flow "up the downer and are forced to percolate through the sieve tray holes. The weir usually cuts some chord length of the column cross section, separating the downer area A_d, from the net area of the sieve tray, A_n (A1 is based on the sieve tray area, not the hole area), as seen in Fig. 2b.

To achieve a given head product purity, thermodynamics will dictate the ideal number of plates, assuming equilibrium is reached. A plate efficiency, E, is used to determine the number of real plates from this ideal case. Plate spacing is usually between 30-50 cm, so column height is then specified. 'typical industrial columns may range from 1/2-2 m in diameter, 5-50 m high.

LUNAR MODIFICATIONS

Dimensional analysis and scaling arguments can be used to modify Earth-based columns for use on the Moon. The prime consideration is the reduction of gravity to one-sixth of that found on the Earth. Gravity-driven buoyant forces are responsible for moving the two-phase fluid system and will affect A_d, A_d, and E. Vapor-liquid thermodynamics will remain the same between the Earth and the Moon so that the number of ideal plates needed for a given separation will remain constant. Hydraulic similarity between Earth-based plates and Moon-based ones should be maintained through dimensional analysis so that the column operation will remain consistent with Earth-bound operations.

In the design of a distillation column, the feed rate and desired component separation are given; column pressure, temperature, number of ideal plates, and reflux ratio are then specified from a blend of thermodynamic and economic arguments. With these parameters fixed, the internal flow rates of vapor and liquid are also known. The column diameter *is* dictated by *the An and* A_d required *to* handle these internal flows, and the height *is* specified by the number of real plates calculated from the ideal number and E.

The net column area A, is correlated to the internal volumetric gas (vapor) flow *rate* Q. The *gas* velocity V_F *is* defined *as* Q_G/An *and is given* by Treybal (1980) *as*

$$V_F = C_F \sqrt{\frac{\rho_L - \rho_G}{\rho_G}} \tag{I}$$

where pL and pG are the liquid and gas phase densities and Cf is the flooding coefficient, a constant determined from the details of plate geometry.

Equation (1) has no theoretical derivation; it is based on empirical correlation of experimental data for the prevention of droplet entrainment in the rising vapor. Realizing that such criterion is based on a balance of forces experienced by the droplets, it is recognized that the)pL -pG)/uG *force between* the liquid droplet and the gas. The density term must be multiplied by g, the acceleration due to gravity, in order to render the quantity into a proper buoyant force, which would certainly result if a theoretical derivation of (1) could be undertaken. Since (1) is developed empirically from Earth-based data, the acceleration due to gravity, which is not considered a separate parameter, would be burled in the flooding coefficient by the mechanics of the correlation process. It is not expected to find the gravitational acceleration anywhere in the equation. Therefore, the effect of gravity must enter in the flooding coefficient, resulting in V_f being proportional to

The terminal velocity of a bubble in liquid (or a droplet in gas) has a well-known solution (Bird et al, 1960) and can be used to reinforce the arguments applied (1), realizing that such analysis is an oversimplification of the actual flooding process. Considering spheriral-shaped bubble

$$F_d = \frac{\pi \rho_L V_B^2 d^2 \theta}{8} \tag{2}$$

will be the drag force Fd, where V_b is the bubble velocity, d is the diameter, and 9 is the than coefficient. The buoyancy force Fb will be as follows

$$F_b = \frac{(\rho_L - \rho_G) g \pi d^3}{6} \tag{3}$$

Equating the drag force to buoyant force and solving for the bubble velocity gives

$$V_B = \sqrt{\frac{4\ dg}{3\theta}\left(\frac{\rho_L - \rho_G}{\rho_L}\right)} \tag{4}$$

For Reynold's numbers greater than 10, which applies to the flow regimes found in plate-type columns, the drag coefficient is constant.

This balance is essentially the same for a droplet falling in gas, except that the density term is *(pL -pG)/pG* because the drag force in (2) is based on the external flow of the medium around a sphere. When applied to a falling droplet, (4) is remarkably similar in form to (1). For the onset of flooding, the gas velocity Vf must be of the order of the droplet velocity, *which* yields *Vf* proportional *to* sqr(g) the *same as* the *result* deduced *from* the empirical correlation *in (1).* Substituting *Qg/A* *for Vf* and solving *for* A_n *gives* the proportion

$$A_n \propto \frac{Q_G}{\sqrt{g}} \tag{5}$$

For the specified feed, reflux ratio, and column pressure, Q will be essentially the same between the Earth and the Moon, so the net area ratio will scale as

$$\frac{A_n\big|_M}{A_n\big|_E} = \sqrt{\frac{g_E}{g_M}} \tag{6}$$

where the subscripts E and M differentiate between the Earth and the Moon.

The scaling *of downer area* A_d will be dictated by the *effects of* gravitational *forces* on liquid flowing downwards in a closed conduit. Considering laminar flow in a vertical pipe, the liquid flow rate QL can be expressed (Bird et al., 1960) as

$$Q_L = \frac{(\pi R^2)^2\ \rho_L g}{\pi 8 \mu_L} \tag{7}$$

where R is the radius and uL, is the liquid viscosity. In general, for a closed conduit, Q, will be proportional to gAd^2 For a fixed volume of liquid flow, will be as follows

$$A_d \propto \frac{1}{\sqrt{g}} \tag{8}$$

which gives the scaling ratio

$$\frac{A_d\big|_M}{A_d\big|_E} = \sqrt{\frac{g_E}{g_M}} \tag{9}$$

From (6) and (9), the lunar values of An and A_d increase by a factor of 2.45 in order to compensate for the one-sixth lunar gravity. For an earthly column I m in diameter, the corresponding lunar column would be 1.6 m

The formation of bubbles with their corresponding interfacial surface area and rising velocity are the most important hydraulic concerns that affect plate efficiency. On a real plate, bubble-liquid interactions are complex. A simplified approach will be used to evaluate the major role of gravitational forces where single bubbles are rising in a body of liquid

Assuming each plate is well mixed, the efficiency can be expressed as the proportion (treybal, 1980)

$$E \propto 1 - e^{-k_L ah/V_B} \tag{10}$$

where E is called the Murphree plate efficiency, kL is the bubble mass transfer coefficient base on the liquid phase, V_B is the bubble velocity, a is the total interfacial surface area, and his the plate liquid depth. Equation (10) yields the ratio

$$\frac{\ell n\,(1-E)\big|_M}{\ell n\,(1-E)\big|_E} = \left(\frac{a_M}{a_E}\right)\left(\frac{h_M}{h_E}\right)\left(\frac{k_L\big|_M}{k_L\big|_E}\right)\left(\frac{V_B\big|_E}{V_B\big|_M}\right) \tag{II}$$

Based on penetration theory, kL for a rising bubble is equal to (Treybal, 1980)

$$k_L = \left(\frac{D_{ab}}{\pi t}\right)^{1/2} \tag{12}$$

where Da_b is the diffusion coefficient and t is a fluid packet-bubble contact time. The contact time will be proportional to bubble diameter divided by bubble velocity, which gives

$$k_L \propto \left(\frac{V_B}{d}\right)^{1/2} \tag{13}$$

The diffusion coefficient is independent of gravity, thus being dropped as an argument Equation (13) yields the mass transfer coefficient ratio

$$\frac{k_L\big|_M}{k_L\big|_E} = \left(\frac{d_E}{d_M}\right)^{1/2} \left(\frac{V_B\big|_M}{V_B\big|_E}\right)^{1/2} \tag{14}$$

which combined with (II) gives

$$\frac{\ell n\,(1-E)\big|_M}{\ell n\,(1-E)\big|_E} = \left(\frac{a_M}{a_E}\right)\left(\frac{h_M}{h_E}\right)\left(\frac{d_E}{d_M}\right)^{1/2} \left(\frac{V_B\big|_E}{V_B\big|_M}\right)^{1/2} \tag{15}$$

The rising velocity of a bubble has already been evaluated in (4) and is proportional to sqr(dg)

The ratio of bubble velocity between the Earth and the Moon will be as follows

$$\frac{V_B\big|_M}{V_B\big|_E} = \sqrt{\left(\frac{g_M}{g_E}\right)\left(\frac{d_M}{d_E}\right)} \qquad (16$$

where the bubble diameter ratio has been included as a possible adjustable parameter.

Consider a bubble forming from gas percolating upwards through a plate hole into a body of liquid. It is important to determine the dependence of bubble mass (hence surface area) to hole diameter and the acceleration due to gravity coupled with the governing fluid properties. In the flow regime for bubble formation typically found on plates, surface tension has the dominating effect with the dependence of fluid viscosity being small. Using the Buckingham Pi method of dimensional analysis, the dimensionless pi group that arises is as follows

$$\pi = \frac{Mg}{\sigma D} \tag{17}$$

where M is the bubble mass, a is the vapor-liquid surface tension, and D is the plate hole diameter. In order to assure hydraulic similarity, this dimensionless group is held constant between the Earth and the Moon, giving

$$\left.\frac{Mg}{\sigma D}\right|_E = \left.\frac{Mg}{\sigma D}\right|_M \tag{18}$$

There are several possibilities for juggling the parameters described in (15), (16), and (18) in order to scale the plates and determine their efficiencies.

Case L Constant Bubble Mass

The most likely choice is to maintain constant bubble mass between the Earth and the Moon, which will assure the same bubble diameter and interfacial surface area for mass transfer. The velocity ratio from (16) will then be the following:

$$\frac{V_B|_M}{V_B|_E} = \left(\frac{g_M}{g_E}\right)^{1/2} \tag{19}$$

and

$$\frac{\ell n\,(1 - E)|_M}{\ell n\,(1 - E)|_E} = \left(\frac{h_M}{h_E}\right)\left(\frac{g_E}{g_M}\right)^{1/4} \tag{20}$$

will be the plate efficiency.

The bubble velocity will be 41% less than that on the Earth due to the one-sixth gravity on the Moon. For the same liquid depth on the plates the contact time will be longer, thus increasing the efficiency and requiring fewer plates for a given separation and a corresponding reduction in column height. The liquid depth could be reduced on lunar plates to maintain the same efficiency, so the number of plates would remain unchanged with plate spacing being reduced. From consideration of plate maintenance and column operation the standard spacings are the most practical, so liquid depth should be kept the same, realizing a shorter column from the increased efficiency. For constant liquid depth, Table I shows typical Earth plate efficiencies and their corresponding lunar efficiencies given by (20), which are enhanced by an average of 25%.

Table I. Earth and Lunar Plate Efficiencies for
Constant Bubble Mass and Liquid Depth

El.	El m
0.4	0.55
0.5	0.66
0.6	0.76
0.7	0.85
0.8	0.92

If bubble mass is to remain the same, (18) can be used to determine the hole diameter in the lunar plates, yielding

$$\frac{D_M}{D_E} = \frac{g_M}{g_E} \tag{21}$$

According to (21), the plate hole diameter for equal bubble masses will have to be six times smaller on the Moon; instead of holes 4-15 mm in diameter, the corresponding lunar perforations will be 0.67-2.5 mm. The pressure drop caused by the smaller holes could possibly increase, preventing the column from operating under vacuum conditions. From Treybal (1980), the pressure drop due to the perforated plate P, is proportional to

$$P \propto \frac{V_h^2}{g} \tag{22}$$

where V_h is the gas velocity through the holes. For holes placed on the corners of equilateral triangles and for equivalent hole diameter to pitch ratios, the increased value of A_n can increase the available hole area, decreasing the gas hole velocity. This can result in a pressure drop on the same order as Earth-based plates. In some instances it may be impossible to specify the smaller holes needed for constant bubble mass without dramatically increasing the pressure drop, making Case I an impractical approach

Case II. Constant Plate Hole Diameter

For pressure drop consideration, the hole diameter in the plates will remain the same between the Earth and the Moon. From (18) the bubble mass ratio will then be as follows

$$\frac{M_M}{M_E} = \frac{g_E}{g_M} \tag{23}$$

which corresponds to lunar bubbles with six times the mass of earthly ones.

It follows from (23) that

$$\frac{d_M}{d_E} = \left(\frac{g_E}{g_M}\right)^{1/3} \tag{24}$$

is the bubble diameter ratio. The interfacial surface area can be approximated by the area of a single bubble times the number of bubbles. For a fixed Q,, the number of bubbles, N, will scale inversely with the bubble mass

$$\frac{N_M}{N_E} = \frac{g_M}{g_E} \tag{25}$$

which gives an interfacial surface area ratio of

$$\frac{a_M}{a_E} = \left(\frac{d_M}{d_E}\right)^2 \left(\frac{N_M}{N_E}\right) = \left(\frac{g_M}{g_E}\right)^{1/3} \tag{26}$$

Using (16) and (24), it follows that

$$\frac{V_B\big|_M}{V_B\big|_E} = \left(\frac{g_M}{g_E}\right)^{1/3} \tag{27}$$

will be the bubble velocity ratio.

For constant hole diameter, the lunar plates will produce bubbles with 1.8x the diameter and 55% of the rising velocity and interfacial surface area. Combining (15), (24), (26), and (27) gives

$$\frac{\ell n\,(1 - E)\big|_M}{\ell n\,(1 - E)\big|_E} = \left(\frac{g_M}{g_E}\right)^{1/3} \tag{28}$$

for constant liquid depth. Table 2 shows the lunar plate efficiencies given by (28). The efficiencies decrease by an average of 34%, primarily the result of a significant decrease in the surface area due to the larger bubble diameter.

Table 2. Earth and Lunar Plate Efficiencies for Constant Plate Hole Diameter and Liquid Depth

0.4	025
0.5	0.32
0.6	0.40
0.7	0.48
0.8	0.59

Case III. Constant Bubble Velocity

Another scaling criterion would be to maintain constant bubble velocity between the Earth and the Moon. From (16), the lunar bubble diameter would have to be 6x larger, which corresponds to a bubble with 216x the mass. Equation (18) dictates a lunar plate hole 36x larger, which does not yield a practical engineering design.

THE LUNAR ENVIRONMENT

The lunar atmosphere has a pressure of 10^-12 torr, which for most considerations is a total vacuum. One would initially think the way to maintain a vacuum distillation process is to utilize the lunar atmosphere as a giant sink, but there are several reasons why this cannot be done. Purging materials into the lunar atmosphere would be a dreadful waste of resources; these materials, especially organics, will be too valuable to lose even a few percent. The void of the lunar atmosphere itself is also a valuable resource (it is noteworthy to point out that the absence of anything can be a resource). Many scientific investigations can capitalize on the combination of a gravitational setting with a vacuum environment, and the scientific value of a lunar base would significantly decrease if this atmosphere were to be contaminated.

Vacuum distillation will be maintained through the use of the cryogenic temperatures available on the Moon. Temperatures as low as 59 K can be obtained through radiation into space. The column pressure is specified by the lowest temperature available in the overhead condenser; in a lunar environment this will correspond to as low a column pressure as desired. Even "fixed gases" like oxygen, nitrogen, and carbon dioxide can be condensed, eliminating the need for vacuum pumps. The extra cost for vacuum distillation will be in the capital equipment needed to handle the radiation heat loads.

An example of a lunar distillation process would be the production of ethanol from fermentation of organic wastes. The column pressure would be maintained so the fermenter functions as a reboiler, where the alcohol is continuously boiled off at a temperature for optimum yeast growth. The azeotrope could be broken under the low pressure so absolute alcohol would be produced. A two-stage overhead condenser would first remove the condensable vapors, with a second-stage cryogenic condenser that condenses the carbon dioxide (as a solid) and any other fixed gases.

SUMMARY

The establishment of a permanent lunar base will offer some interesting possibilities for the design of distillation processes. The lunar environment will make possible convenient vacuum distillation and will facilitate column insulation. For a lunar column, the net plate and downer areas will increase by a factor of 2.45. The lunar plate efficiencies will either increase by about 25% (for constant bubble mass) or decrease by 34% (for constant hole diameter), the choice depending on the imposed engineering constraints.

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TOWARD A SPARTAN SCENARIO FOR USE OF LUNAR MATERIALS

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Many lunar materials have been proposed as raw materials for space manufacture. Only those that are abundant and extractable by relatively simple means may be feasible for use. These include mare and highland soils and very abundant rock types. Even the restricted set of materials and extraction processes considered can yield a good variety of raw materials.

INTRODUCTION

Visionaries seeking to show in general terms how our space environment can be used to our benefit have every justification for assuming the usefulness of the chemical elements available on the Moon or on other bodies in the solar system. Those proposing more specific uses of extraterrestrial materials should feel obliged to learn in detail the nature of the materials as found and to determine whether their strategies for use are reasonably based on material availability and probable economy of manufacture. In particular, it falls to the chemist, the chemical engineer, and the metallurgist to test the technological feasibility of individual stages of grander scenarios for product development from space resources.

If lunar ores and conditions resembled those on Earth, it would be straightforward to transplant terrestrial technology to the Moon's surface. Since they do not, it is necessary to consider whether it is better to try to adapt terrestrial technology to the Moon's very different conditions or to devise fresh technologies appropriate to them. This debate may continue for some time, as little research has been done so far to enable choices to be made. The best techniques for converting lunar materials to useful products may not even have been thought of or recognized yet, as we have little direct experience in coping with the space and lunar environments. We still tend to view most extraterrestrial conditions as obstacles and have not learned to react intuitively to them as the advantages that, for many purposes, they will surely be. At the very least, we owe it to ourselves to determine, at the laboratory bench scale, the basic characteristics of all the extraction and manufacturing processes we can conceive of during the next several years before choices must be made on whether to employ lunar matter for use in space and if so, how.

Some proposed scenarios for manufacture seem to be based on misunderstanding of the nature of the starting materials or to demand for their execution outlandish layouts of factories, prepared reagents, and energy. It is better to use lunar materials instead of terrestrial ones only if there is significant gain in economy or time by doing so. There is, nevertheless, reason to be confident that the combination of those products that can be produced relatively simply from lunar materials for use in space will prove to be economical, will accelerate the growth of space activities, and will enrich human welfare and experience.

The purpose of the discussion below is to identify those raw materials for use in manufacture that can most readily be obtained from lunar materials as we know them. Availability of lunar materials has been considered by others (eg., Williams and Jadwick, 1980; Williams and Hubbard, 1981; Arnold and Duke, 1977; Arnold, 1984). Information on the nature of the materials found on the Moon is summarized by Taylor (1975) and the details are found in the many volumes of the Proceedings of the Lunar and Planetary Science Conferences. The state of lunar exploration is incomplete, and there is reason to believe that concentrated ores may exist for elements that must now be regarded as rare or dispersed. The discussion here, however, describes minimum possibilities, based on the notion of making do with the least feasible amounts of separation and processing.

This ground rule will not necessarily lead to the most likely scenarios for space manufacture using indigenous materials. Utilization of lunar resources is complicated sufficiently just by the difficulties of transportation and living that any such manufacture is necessarily somewhat complex, and the best methods may need to be *very* complex to be economical. There nevertheless seems to be merit in asking what is most easily available. Besides, there is a certain satisfaction in imagining oneself to be a lunar homesteader trying to adapt to the Moon's environment with as few fancy tools and as little dependence on support from home as possible. As seen below, it appears that a substantial range of materials can be obtained with minimal separation and that scenarios based on the simplest technologies are not severely restrictive.

GROUND RULES

For this discussion, we limit ourselves to the most abundant materials observed at lunar sites visited by the Apollo missions. Excluded from consideration are less abundant materials already known, conceivable exotic ores, and hoped-for polar water. Materials are to be used directly for manufacture in "as found" condition or high-graded or separated by only the simplest means.

Although manufacturing processes are not considered here, corresponding constraints can be defined for them. For example, manufactured products should be used on the Moon or in space, not on Earth; however, any complex components would be imported. Steps in manufacture would have to be few, easy, and reliable.

These constraints, in turn, can be accompanied by ground rules for use of lunar products. Materials used in space will be those available and adequate, not necessarily those traditionally used, envisioned, or preferred on technical grounds for a given application. The quality of materials used will not necessarily match those of similar materials produced on Earth; sizes and quantities needed must be adjusted accordingly. Assembly and application of products of space manufacture must be simple and rapid and tolerances relatively loose.

TOOLS

The tools necessary to carry out any significant production of raw materials for manufacture cannot be regarded as simple, but merely as relatively simple. One item will have to be dirt-moving equipment, necessary for habitat excavation, as well as for transporting feedstocks to smelting or manufacturing sites and removing waste products and, perhaps, the products themselves. It is assumed that all processes, from gathering and production of raw materials through manufacture and assembly, will be substantially automated. Equipment probably will be tended, mainly from remote stations nearby. Equipment should be designed to allow straightforward repair, optimization to actual encountered conditions, and innovative adaptation by the operator to new feedstocks and conditions.

Electrical power, at least one megawatt, will have to be available for any significant processing or manufacturing activity. Initially, this probably will need to be nuclear power, although eventually solar power should be exploited to the fullest extent Through the use of concentrating mirrors, solar power should be available at the outset for heating of materials to high enough temperatures to melt or even distill them.

LUNAR SURFACE CONDITIONS

The lunar surface is a source of high and unavoidable vacuum, both an inconvenience and a potential aid to manufacture. The acceleration of gravity is only one sixth that of Earth, which makes strengths of materials less of a problem for lifting and supporting, although not for withstanding changes in momentum. Also, the microgravity of orbiting factories can be used for processing lunar material, where appropriate. Half the time, the lunar surface is bathed in sunlight, without uncertainties from clouds; each day and night is about 328 hours long. Surface temperatures range from roughly -170°C in the shade to +120°C in direct sunlight. There is no medium for heat exchange as on Earth where abundant water and air are available, so waste heat must be dissipated by radiators. Sunlight is available nearly full time in orbit, and lunar bases at polar locations might also achieve full-time use of solar energy. The lunar surface abounds in fine dust, a convenient form of rock for some uses but a potentially serious problem for operation of equipment and for personnel comfort and health.

READILY AVAILABLE MATERIALS

Unprocessed Regolith

The material most readily available is unprocessed lunar soil (McKay, 1984). This consists mainly of fine rock flour (Papike, 1984), produced by past impacts of meteorites on the atmosphereless lunar surface. Some of the particles have been melted during impact and are present as glassy agglutinates. As encountered, this rock flour contains fragments ranging in size from clay to boulders. The minimum high-grading would consist of sieving out the larger fragments. Soils at mare sites are made mainly from crushed lunar basalt, similar in nature to common terrestrial basalt but drier and chemically more reduced. Fragments in mare soils are rich in the minerals plagioclase feldspar and pyroxene with ilmenite an important minor component. These minerals are not mainly present as separate grains, but are joined together as rock fragments or mixed and partly melted to make glassy agglutinates. From an elemental point of view, these soils are rich in oxygen (41%) and silicon (19%) (as are all known lunar soils), and in iron (13%), magnesium (6%), and, relatively, titanium, (up to 6%). Soils derived from highland rocks have lower abundances of iron and magnesium, but tend to be rich in aluminum (14%) and calcium (11%).

These elements do not occur in elemental form but in combination with oxygen. Their compositions are usually reported in terms of idealized oxides based on the probable oxidation state in the rock. It must be recognized that the concentrations as given are not intended to imply the presence of the oxides as such; the elements and their shares of oxygen are present as solid solutions, i.e., as the minerals, mainly silicates, from which the rocks are made.

Most soils in mare regions appear to contain significant quantities of highland rocks, probably because many mare deposits are rather shallow and have allowed craters of intermediate size to penetrate into their highlands substrates. Soils distant from maria seem to have rather small percentages of mare components. Mixed soils, found mainly near mare-highland boundaries, have intermediate compositions.

In addition to the soils there are rocks. While perhaps not in as convenient a form to use as the already pulverized soils, they offer the possibility of more concentrated sources for some elements. Some rocks found on the Moon's surface are nearly monomineralic. These include anorthosite (nearly pure plagioclase feldspar, a calcium aluminosilicate) and dunite (nearly pure olivine, an iron-magnesium orthosilicate solid solution). Similarly, certain mare basalts are richer in titanium than are the soils derived from them. Not enough is known about the highlands to determine whether any monomineralic rock is present in sufficient abundance to serve as a convenient source of ore. Dunite fragments are rare at Apollo sites. Anorthosite fragments are abundant at the Apollo 16 site and were found also at the Apollo 15 site as isolated pieces in the regolith or as large clasts in breccia boulders. Breccias are rocks composed of broken fragments of prior rocks, compressed together to produced mixed rocks. Breccias are overwhelmingly the most common type of rock collected in the lunar highlands. Other rock types fairly common as clasts in breccias from the highlands are troctolite (olivine-plagioclase rocks) and norite (pyroxene-plagioclase rocks). Remotely sensed infrared spectra indicate that the central peaks of some large craters may be principally olivine and of other craters principally plagioclase (e.g, C. Pieters, personal communication, 1984). This is unconfirmed by sampling since no such sites were visited by the Apollo or Luna missions. However, the soil at the station 11 site, Apollo 16, is highly enriched in anorthosite. By far the most common compositions observed by infrared remote sensing are those corresponding to norite, the same compositions that are typical of bulk or average samples of highland breccias (B. Hawke, personal communication, 1985)

Minimally Processed Regolith

There is some metallic iron, commonly about a tenth of a percent, in lunar soils. It is mainly present as fragments from meteorites that broke apart during crater-forming explosions and became mechanically mixed with lunar rock debris. It consists of alloys of iron that contain up to several percent nickel and some cobalt. This metal can be high graded by simply drawing a magnet through the soil. Pure metal will not be obtained, however, because many fragments are incorporated into agglutinates, which are glassy shards produced by melting of soil during meteorite impacts. Also, there are small amounts of indigenous metallic iron in lunar igneous rocks, a reflection of Moon's dearth of free oxygen. When bits of such rocks are incorporated into agglutinates, they contribute to their magnetism. A magnet gathers both magnetic agglutinates and metal fragments, and further processing to obtain pure metal would have to be done.

Within most lunar soils at least a few percent of the fragments are grains of single minerals. The percentage can be fairly high when the rocks from which the soils derived were coarse grained (e.g., anorthosites) so that even sizeable fragments can be essentially monomineralic. It is lower but not negligible in soils derived from finer grained rocks (e.g., basalt), because soils tend to be so finely pulverized that many of their grains are monomineralic fragments. All grains do not become monomineralic, because the micrometeorite-driven processes of partial melting and agglomeration to produce agglutinates work against continued communition of soil grains. Electrostatic processing (Agosto, 1984) offers the possibility for separating some minerals (e.g., ilmenite) in highly concentrated form, potentially useful for providing special feedstock. Residues from this processing are also available and will have properties different from those of the bulk soil. Since these residues must be handled anyway, it is desirable to find uses for them and to control their properties as much as possible to provide for good secondary products. Most separation processes produce several different fractionated materials.

Melting of common lunar silicates can produce a variety of glasses with different properties. These can be cast or drawn, and under water-free lunar conditions may have great tensile strengths (Blacic, 1984). Speculation on possible products (Steurer, 1984; Khalili, 1984) and their properties is beyond the scope of this discussion of raw materials; glasses are mentioned here because they can be produced by such simple processing.

MAXIMUM "ALLOWED" PROCESSING

Herein, we offer a few examples of processing methods we regard as the most complicated allowable for serious discussion in realistic planning for an initial Moon base. Any of these processes will require substantial engineering and equipment to carry out. Along with the products of interest, we call attention to the residues, which may themselves have application.

Thermal Release of Gases

The simplest scheme for production of gases involves heating of lunar soil to release trapped solar wind. The most abundant implanted elements that can be extracted in this way are hydrogen, helium, nitrogen, and carbon. Since concentrations of these elements are low (mainly 50-100 parrs-per-million by weight), large volumes of soil must be heated for a reasonable yield. The elements are tightly bound within surfaces of soil grains; soils must be heated to temperatures of 700-1100 °C to release them. Provided that the tonnages of fines can be handled adequately, useful amounts could be obtained Some indigenous, relatively volatile elements such as sulfur, chlorine, and noble gases (mainly argon) are similarly abundant in some soils and could also be extracted by heating. The products of heating of materials from indigenous and solar -wind sources would include water, hydrogen sulfide, carbon monoxide and dioxide, ammonia, and hydrogen cyanide, among others. For efficient handling, these gases may require oxidation (with lunar derived oxygen) to produce three readily separable fractions: water, carbon dioxide, and nitrogen plus noble gases. The available quantities of entrapped solar wind are sufficiently high and the economies of complete propellant production on the Moon so appealing that production of hydrogen deserves serious consideration (Carter, 1984; Friedlander, 1984; Rosenberg, 1984; Danford et al., 1984). The problem of heating large tonnages of lunar soil in a closed system to capture emitted gas has not received adequate consideration. The residue would be degassed lunar soil, or, if melted, glass.

Ilmenite Hydrogen Reduction

The gaseous product that has received the most consideration so far is oxygen (e.g., Rosenberg *et al.,* 1965; Driggers, 1976; Davis, 1983; Carroll *et al.,* 1983; Cutler, 1984a,b,c; Kibler *et al.,* 1984; Gibson and Knudsen, 1984; Waldron, 1984). Extraction of oxygen requires oxidation of that element from an oxide (e.g., ilmenite) or from silicates (e.g., mare basalt; separation of a pure silicate mineral does not seem necessary). The method receiving the most attention is one in which the water is electrolyzed and the hydrogen returned for further reaction (e.g., Williams and Mullins, 1983). The ilmenite concentrate would have to be provided by highgrading of lunar soil as described in the previous section, and in that sense the "ilmenite process" is at least a two-stage process. The residue would be an intimate mixture of iron metal and unreduced iron oxide and titanium oxides, plus perhaps some silicate, depending on the purity of the ilmenite concentrate
and Volk, 1965). Electrolysis of molten silicate and other processes are also being considered for oxygen production (e.g., Kesterke, 1971; Lindstrom and Haskin, 1979). None of the proposed processes is adequately understood yet at the laboratory bench scale.

Carbonyl Processing

The carbonyl process has been studied extensively, used industrially on Earth, and considered for use in space (e.g., Lewis and Nozette, 1983; Lewis and Memel, 1984). It should be relatively straightforward to use it to extract the metal concentrated magnetically from lunar soil and, in the same sense as the ilmenite process, would be part of at least a two-stage operation Possibly, it could extract metal from unbeneficiated soil. The principal product would be high purity iron, and a secondary product would be high purity nickel. Cobalt and heavy noble metals will also be extracted In such high purity, iron metal may attain remarkably high strength (Sastri, 1984). The residue would be mainly metal-free or at least metal-poor silicate. Carbonyl extraction of iron in the residue from hydrogen reduction of ilmenite has been demonstrated and required carbon dioxide pressures of 100-150 atmospheres and catalysts such as hydrogen sulfide for efficient separation (Vlshnapuu et al., 1973).

Electrolysis of Molten Silicate

Electrolysis of molten silicates to produce oxygen gas has the attraction that it requires, in principle, only sunlight for heat and electricity and lunar soil as its feedstock (e.g, Lindstrom and Haskin, 1979). Experiments using simulated lunar basalt show that, while oxygen is being liberated at the anode, iron metal is simultaneously formed at the cathode, possibly as an alloy containing small amounts of chromium and manganese and with other impurities. Ilmenite-rich compositions yield iron metal alloyed with some titanium; titanium-poor compositions can yield iron alloyed with silicon. Since compositions of silicates can be significantly changed as a result of electrolysis, this method can leave residues with compositions different from those of indigenous lunar materials. It is perhaps not proper to regard the silicate residue as a residue, since the silicate melt might be the primary product of electrolysis.

Destructive Distillation

Solar furnaces are capable of producing very high temperatures. Some experiments have been carried out on meteoritic material (e.g., King, 1982; Agosto and King, 1983), but no systematic study has been made on condensates or residues from the destructive distillation of simulated lunar silicates. The most refractory material formed probably would be calcium aluminate or, perhaps, calcium oxide. Extraction of gases, discussed above, is a relatively low-temperature form of destructive distillation of silicates. At higher temperatures, even perhaps during gas extraction, other useful substances such as alkali metal oxides might be concentrated by volatilization.

CONCLUSIONS

Unprocessed lunar soil can be used for radiation shielding both on the Moon and in space. Numerous glass products can be made, perhaps with special properties resulting from the dry lunar and space environment; these may become the principal structural materials for space. Iron and nickel can provide steel products, including electrical conductors. Ultra-pure lron may be as good as steel for many purposes. Oxygen and perhaps hydrogen gases can be produced for propellant and life support This is a very good list of potential early raw materials for use on the Moon or in space. Much work still must be done to determine the conditions required for development of even simple procedures for obtaining and using these raw materials. The constraint of keeping things simple (relatively) does not seem to be an uncomfortably restrictive one.

Acknowledgments *Some of the ideas presented in this paper were developed* during *a NASA-sponsored summer* workshop entitled *Technological* Springboard *to the* 21st *Century, held in 1984 at the University of*

California in San Diego. Discussions *at the workshop with M Duke and S. Sash are gratefuly* acknowledged This work *was supported in part by* the *National* Aeronautics and *Space* Administration through *grants* MAGI* *179* and NAG-9-56.

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LUNAR MACHINING

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Chip-making machine tools have traditionally been used to shape iron Regolith is several tenths percent iron nodules by mass, which could be melted by solar process heat, then cast Chip-making machine tools may well be used to further shape these castings little serious consideration has been given to machine tool design within a lunar context, however. This is a first survey of the problems and opportunities of lunar machining. A conceptual framework for machine tool design is given, then applied assuming lunar operations It is that there will be a need for small machines operating in shirtsleeve environments, that larger machines will have to be outside in vacuum because they require large, rigid foundations that can sink vibration, and that productivity will be extremely important due to very high labor costs

Serious consideration is being given to the establishment of a lunar base during the first half of the next century (von Puttkamer, 1976; Duke, 1984). Whether a scientific, industrial, or growth rationale is selected, machine tools will almost certainly be used at the base site. Machine tools may first be used in repair and maintenance of the base itself. Later, more machines might be brought in as support for construction of scientific instruments, construction of industrial plants, construction of more habitats, and manufacture of capital goods.

It is of some intellectual and practical interest to consider the design challenges that must be answered before machine tools can be used in a lunar environment. This short paper will content itself with identifying design challenges and opportunities. Ways of meeting them will be treated only briefly.

KINDS OF MACHINE TOOLS CONSIDERED

Many promising means have been proposed for production of industrially useful raw materials in the lunar environment. The basic physics of the environment are well described in *Advanced Automation for Space Missions* (Freitas and Gilbreath, 1982). Several specific processes have since been proposed, including vitrification of lunar soil (Meek et al., 1984), production of glass fiber cables (Steurer, 1984), production of metal powder (Criswell, 1983), and the carbonyl process (Steigerwald, 1984; Lewis and Meinel, 1983). Fabrication of these raw materials has received less attention, although high technology methods have been discussed, such as David Criswells work concerning powder metallurgy technology (Criswell, 1983) and an intersecting beam method of mold fabrication coupled with powder metallurgy suggested by David Brin (personal communication, 1984; Schwerzel et *dl,* 1984).

Lunar soil is several tenths of a percent iron spheroids that can be magnetically separated from regolith (Arnold, 1984). Iron may also be a by-product of lunar oxygen production (Cutler, 1984a,b). Furthermore, chip-making machine technology is reliable, simple, and mature. It was the critical manufacturing technology of the Industrial Revolution 200 years ago. It is thus a prime candidate for use under the primitive conditions that will characterize early lunar industry (Cutler, personal communication, 1984).

This paper will consider adaptation of chip-making machines to the lunar environment. It will emphasize adapting the lathe and the milling machine, which may encompass most significant challenges. Iron mining, extraction, and casting are beyond the scope of this paper.

PRINCIPAL DESIGN FACTORS OF MACHINE TOOLS

On Earth, the principal machine tool design factors may be thought of as precision, power, and economy (Doyle, 1961). These are apt to remain the principal factors on the lunar surface. Precision depends on avoidance of inaccuracy in construction, deflection under static or dynamic load, wear, and thermal expansion.

Inaccuracy in construction is avoided through careful control of factory environment and operations, use of precision machine tools, and careful inspection after each stage of manufacturing.

Deflection is minimized by rigidity and properly chosen natural frequency. Deflection can be caused by static loading, due to workpiece and frame weight, and also by dynamic loading, usually caused by eccentric rotation of a mass. Of the two, dynamic loading is usually the greater challenge, as it can cause large amplitude vibration if it is at the natural frequency of the machine tool's frame.

Static deflection is often minimized by massive iron alloy frames, which, for larger machine tools, are coupled to massive concrete foundations.

As a rule of thumb, dynamic deflection can be minimized by a combination of rigidity, low mass, and damping that gives the machine tool frame a natural frequency at least (4 is better) times that of the highest exciting force frequency. Alternatively, a combination of rigidity, high mass, and damping can give the frame a natural frequency less than 1/J (1/4 is better) that of the lowest frequency exciting force frequency (Tobias, 1965). However, the spectrum of the exciting force depends largely on the angular velocity of the eccentric mass, which varies during machining. Exciting force frequencies from 0-4000 Hz are commonly encountered during machine start-up and operations (the higher frequencies come from impact loads or gears), and an exciting force spectrum can have several peaks. The frame's natural frequency can also change with machine configuration.

On Earth, an industrial machine tool is rigidly attached to a massive, rigid foundation. If this is not possible, it is attached to a vibration isolation system. This drastically reduces the machine's natural frequency. Typically, one tries to put the natural frequency of the isolation system as far as practical from the nearest peak in the exciting force spectrum characteristic of normal operation and relies on damping to soak up noise and transient resonances during start-up. If the isolation system needs augmenting, dynamic deflection of the machine tool can be reduced by vibration dampers (Tobias, 1965) that dissipate vibrational energy most effectively over some narrow frequency range.

Wear of precision-located sliding way surfaces is reduced by hardened steel ways, by dirt shields, and sometimes by plastic inserts in which chips become embedded before they can damage the ways. Avoiding wear of precision-located shafts may involve a pressurized lubrication system or roller bearings. Should wear occur, it could make the precision surface curved, or could worsen fit and introduce motion hysteresis in the force vs. motion curve. It is difficult for a control system to compensate for either of these. Wear also promotes chatter and vibration with consequent degradation of workpiece surface finish and possible fracturing of the cutting insert. Should significant wear occur, the worn surfaces must either be restored or the machine must be discarded.

Thermal expansion is avoided by not exposing the machine tool to direct sunlight and keeping ambient air at a constant temperature. Of these two, shielding from sunlight is the more important, because local heating can distort the frame. Constant ambient temperature becomes important for precise work such as metering nozzle fabrication.

Power is provided by electric, hydraulic, or pneumatic drives. Conventional drives are bulky and frequently cannot be connected directly to the load. Mechanical energy must be conveyed from drive to load by mechanical elements. For rotary motion, gears and belts are commonly used. For linear motion, the pinion and rack, the screw and nut, and the crank are commonly used. All of these mechanical elements add flexibility, stick slip, and, frequently, force vs. motion hysteresis. Such effects are minimized only by maintenance of very small tolerances, which make these elements difficult to produce, hence expensive.

Economy of operation involves proper operating controls, provisions for safety, and facilities for changing jobs. Operating controls have tended to become increasingly automatic, so that for some systems of machine tools no direct labor is required, only monitoring. Safety features also have tended to involve automatic operation. job changeover is a surprisingly important part of machine economy. The machine produced nothing during changeovers, so changeover time must be minimized. Contemporary practice favors use of pallets, downloading NC programs, and various shop floor control methods. General purpose machines tend to change over more rapidly than special purpose machines, accept a wider range of work, and are idle less. Conversely, they cannot be made as rigid as special purpose machines, and hence they remove metal more slowly.

Economy in construction and maintenance may involve the use of standardized component parts, such as the base, headstock, or saddle. These can be combined at times in novel ways to produce a special purpose machine tool.

This is summarized in Table 1, Primary Challenges.

ADDITIONAL DESIGN FACTORS FOR THE LUNAR SURFACE

Precision, power, and economy will be just as important on the lunar surface as they are on Earth but may be designed into the tools differently. Let us first consider the unique characteristics of the lunar operating environment.

Pressure Vessels

A large machine tool must generally be fixed to a massive foundation that provides rigidity and couples vibration to the soil. Such large tools cannot be simply bolted to

Table 1. Primary Challenges

Precision:
- Vibration (grounding or isolation and damping)
- "Unsagging" in reduced gravity
- Wear (in vacuum operation)

Power
- Heat dissipation
- Energy source (beyond scope of this paper)

Economy:
- Labor requirements
- transportation costs from Earth

a pressure vessel They would distort under load, lose accuracy, and shake the entire vessel. These effects are especially pronounced at low cutting speeds, which generate *high* cutting forces at low frequency. The cutting forces can be reduced by use of lubricating cutting fluid or a modified cutting tool geometry (Trent, 1977).

Smaller machine tools do not require rigid foundations. Resilient supports can be placed directly between the machine tool and the shop floor if the exciting forces are small in comparison with the machine tools' weight and if the machine tool frame is sufficiently rigid. In most cases, these supports need not even be fixed to the floor, since hardly any dynamic force is developed at the point of support (Makhult, 1977).

If the natural frequencies of the pressure vessel can be determined, vibrational dampers tuned to these frequencies can be added. Practical dampers frequently use rubber for the spring/dashpot. Effectiveness depends on many factors, including the natural frequencies of the machine tool, the spectrum of the exciting force, and the range of movement tolerable in the damper (Tobias, 1965).

Environment within the vessel is affected by debris from the machine tool. This includes vapor and droplets of cutting fluid, ozone and heat from electric motors, chips and chip fragments, lubricant vapors, and the many other things that make a machine shop a messy environment, wherever it may be. High accuracy operations require constant air temperature. This should be part of the base thermal control system's design criteria

Vacuum

If a machine tool is operated in vacuum, heat dissipation by convection cannot occur. Heat dissipation by conduction and radiation is typically less efficient than convective cooling. Most of the waste heat from chip formation stays in the chip and thus will probably not be a serious problem (Trent, 1977). Heat dissipation from power and control units could be a challenge. Finally, exposure to direct sunlight could cause significant local heating and thermally warp the frame.

vacuum operation could also create unoxidized free surfaces, particularly during chip formation. If the surface freshly uncovered during chip formation is not exposed to an oxidizing agent, chip-tool relations are changed. Edward Trent (1977) observed substantial increases in chip thickness and in cutting force when machining iron at atmospheric pressures below 0.001 mbar, apparently due to a substantially increased area of contact between chip and tool. Introduction of air, even at very low pressure, eliminated this effect. Trent suggested that unoxidized free surfaces seize against the cutting tool more strongly than do oxidized surfaces.

Wear at exposed bearing surfaces could lead to vacuum welding and rapid failure. Contamination by lunar dust is an additional environmental hazard On the other hand, deliberate creation of precision unoxidized free surfaces in conjunction with locator pins/holes could permit use of vacuum welding in construction of structures.

Gravitational Field

Reduced weight in the weaker lunar gravitational field will reduce frame self loading and will reduce the resulting sag to 1 /6 of its Earth value (assuming elastic deformation and superposition). If a complex geometry superimposes several strains, a significant loss of accuracy may result. Machining forces are fairly small [several tens or hundreds of Kgf or Ibf, several thousand N (Trent, 1977)] compared to workpiece weight, which is at most comparable to frame weight. Wayne R. Moore, a machine tool designer and fabricator, has put together a very interesting book (Moore, 1970) on machine tool accuracy. He emphasizes the importance of inspecting and correcting high precision machines under expected conditions of use and the importance of appreciating droop caused by cantilevering. Reduction of frame self loading could cause precision linear surfaces machined into the top of cantilevered frame members to curve upward into a ski jump shape. This could be significant for large or very high precision machine tools.

Workpiece weight will also be reduced. The primary effect may simply be to ease loading and unloading, since fixturing and not workpiece weight holds the workpiece to the work table. However, an eccentrically mounted, massive, and rapidly rotating workpiece could conceivably throw itself and an unsecured machine tool off its foundation in 1 /6 g.

Reduced acceleration of freely falling bodies in lunar gravity will affect dispersion patterns of debris leaving the machine tool. Chip and cutting fluid dispersion would be increased. More seriously, rotating parts released through latch failure would travel further or would hit overhead surfaces at greater velocity than on Earth.

Transportation Costs

Transportation costs to the lunar surface are thought to be in the range of $3,000 to $15,000 per kilogram (Duke, 1984). While not directly affecting precision or power, these costs will have a strong influence on machine tool design. One could design very light and compact machine tools, or design heavy machine tools and fabricate the most massive components from lunar materials on the lunar surface.

Transportation costs will determine labor costs. People must be transported to the lunar base, and until controlled ecological life support system (CELSS) technology is developed and applied, their food must be brought up from Earth as well. The labor pool will accordingly be small. An initial base complement of something less than 20, and perhaps as few as 2, seems plausible. Support facilities will be less developed than those on Earth, including both recreation and training facilities. Additionally, work in a vacuum will involve either pressure suits or teleoperators, both of which reduce effectiveness. Work inside pressure vessels could be hampered by limited area and volume. The net result could be a small, expensive, but not very productive work force. Automation, teleoperation from Earth, and attention to habitat design could increase work force fitness.

Transportation costs will also determine material supply costs. Spare parts from Earth will be expensive, as will consumables such as cutting inserts, cutting fluid, and lubricants. Importation of an adequate *inventory* may well be deferred indefinitely. In the worst case, one could combine highly expensive repairs with long waits for spare parts. Proper *attention* to *inventory* requirements during planning will be essential.

Lunar design challenges are described in Table 2.

Table 2. Recommendations

Vibration:
- Operate smaller machines inside pressure vessel and isolate/damp vibration.
- Operate large machines in vacuum and sink vibration into massive foundation

Unsagging:
- Correction if necessary at the lunar base.

Wear (in vacuum):
- Avoid vacuum welding.
- Avoid lunar grit contamination.

Thermal environment
- Avoid sunlight in vacuum operation.
- Keep air temperature constant for high precision work in pressure vessels.
- Alternately , fabricate machine tools from zero coefficient of expansion composite material.

Power.
- Consider heat dissipation in base thermal budget and in machine design.

Economy:
- Automate or teleoperate material handling setup, and operation to minimize labor requirements
- Minimize transport cost by designing light machine tools or fabricating some machine tool elements at the lunar base.

DISCUSSION

The design challenges for a lunar base suggest that there will be two classes of machining: light duty machining inside and heavy duty machining outside. Light duty machining will be needed Tor base maintenance. Fortunately, inside, light duty machining requires only the design of a light duty, vibration isolated/damped, general purpose, but productive and accurate machine tool Heavy duty machine tools pose more of a design challenge. They must operate in vacuum, require minimal oversight, and involve minimal haulage costs from Earth.

Technology Mix

The design challenges listed above are not those of Earth; consequently, we can expect a different technology mix In the early days, the lunar machine tool will be entirely Earth-made and will combine low mass, reliability, versatility, and high productivity with high purchase price and a limited work volume. It may employ conventional technology within these limits, or may employ unusually high levels of automation, composite material, and unusually high power, high torque electric motors. The design goal would be to maximize productivity and minimize mass and shipping bulk.

From the second generation on, machines could be made partly on the Moon and partly on Earth. The economic issues here are more complex than may at first be apparent. Goldberg and Criswell (1981) have considered the general case. For the specific case of machine tools, the "make/buy' decision on the Moon will primarily involve the number of hours required to make an item, the marginal cost of these hours, the mass and geometry of the item to be made, the marginal cost of shipping this mass and geometry, and (as a secondary consideration) the salary of the people doing the work and the cost of the item if bought. Ordinarily, these discussions would be dominated by the primary considerations; one would choose the cheaper of marginal labor and marginal shipping. If assembly is feasible, one would expect massive parts to be made on the Moon [a 37 kW 127-cm swing lathe masses about 21,400 kg (Doyle, 1961), most of which is frame] and precision parts, electronics, software, motors, and other goods whose manufacture requires extensive industrial plant, to be brought from Earth. The lunar machine tool may thus, in the medium range, be a mix of sophisticated, low mass components brought from Earth and very crude, but high mass components made at the lunar base.

Drivers

Over time, one can say that the technology mix will be driven first by labor costs, then by shipping costs from Earth, and eventually by material import costs. These different drivers will give rise to a mix of sophisticated and crude technologies that, however inappropriate they would be on Earth, will be quite functional on the Moon.

Side Effects

Lunar machine tools will generate seismic waves and will emit gases and vapors. These effects would not materially add to those of a moderate-sized (20-person) lunar base with supply rockets, construction equipment, and mining operations. A small, vibration isolated machine tool should have few or no significant side effects if kept in a pressure vessel.

SUMMARY OF RECOMMENDATIONS

The lunar environment poses unique, but partially predictable, challenges in machine tool design. The primary initial challenge appears to be the design of a light duty, small table, ultralight, ultrareliable, ultraversatile, vibration isolated, vibration damping, numerically controlled machine tool to be operated in a shirtsleeve environment for base maintenance. Jt might machine parts of up to 1 foot (30 cm) in longest dimension. This machine will be needed soon after the establishment of a permanently manned base.

A second challenge appears to be the design of a large, light, ultrareliable, numerically controlled lathe to be operated on a massive foundation in a vacuum. It might have a 30-inch (76-cm) throw, 7 feet (2 m) between centers and require 25 kW Operation of this machine must be automated to the maximum extent possible. Consideration should be given to artificial intelligence, robotics, teleoperation from the lunar base, and teleoperation from Earth. If several are installed, attention should be given to material handling between machines.

The large lathe could machine massive frames for small rolling mills, supports for solar furnaces, and frames for unpressurized but radiation-shielded work areas. It could machine and polish large iron mirrors for a solar furnace. It could, in conjunction with the light duty machine tool, make most elements of crude, but effective, machine tools. Much of the mass in lunar industry would be in such elements.

Table 3 describes a starter kit that could address the first two challenges.

Table 3. 'starter Kit

- First, introduce a small, tight duty, versatile machine tool for use inside base for maintenance and repair.
- After base is well established, introduce a large, heavy duty machine tool for use in vacuum, to machine large structural elements.
- Machine iron castings to make frames for mining equipment, machines, solar mirrors, machine tools, and other massive capital goods. This will require both the small and large machines above. Import fittings from Earth, assemble on Moon.
- Benefit is greatest for more massive frames and smaller assembly and machining times.

The final foreseeable challenge is expansion. Processes will become less crude and the range of available materials higher as the economy grows. This will mark the emergence of a self-sustaining lunar economy using lunar materials, a springboard to a true lunar industry and a true lunar society.

Acknowledgments *Many* thanks *are due* to *the* NASA *Summer* Faculty *Program* and the *California Space Institutq which were responsiblefor* my *introduction to this area of study and for several of the ideas* presented *above*

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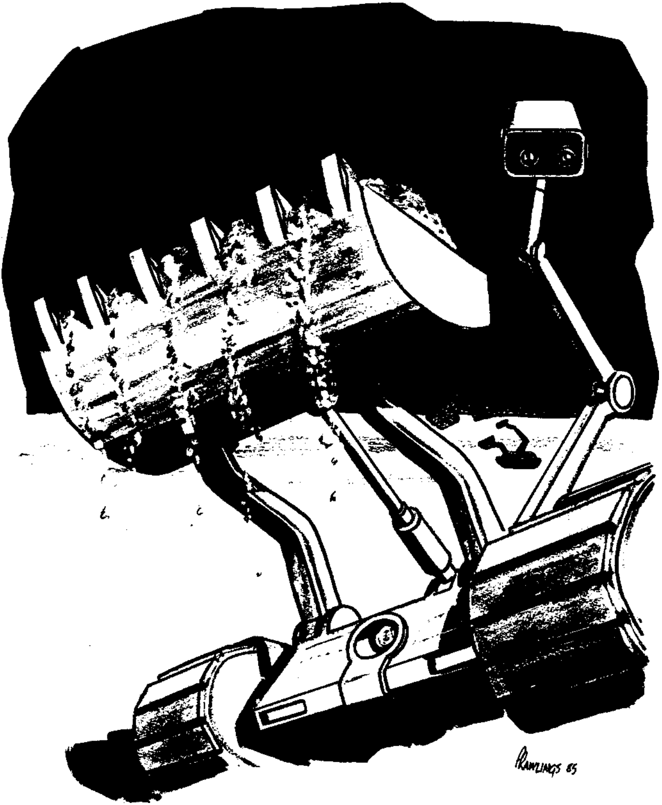
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A LUNAR-BASED PROPULSION SYSTEM

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As activities in cis - and trans-lunar space and on the Moon increase during the 21st century, the use of a lunar-based propulsion system, refueled by propellants manufactured from lunar resources, may offer large cost savings when compared with a space-based propulsion system refueled from the earth. Oxygen/hydrogen (LO_2/LH_2) bipropellant propulsion appears to be attractive because of its estimated hlgh delivered specific lmpulse, i.e, 485 s. However, difficulties associated with the long-term storability and low density of lH_2 detract from this performance. Other bipropellant combinations may have advantages in this context The potential utility of the oxygen/silane ($LO_2/LSiH_4$ blpropellant combination for use in a lunar-based propulsion system and the potential for the on-site manufacture of Lunar oxygen and share are considered in this paper. It appears that oxygen and silane can be produced from common lunar mare basalt in an integrated fatality. The carbothermal process uses lunar materials efficiently to produce oxygen and silane-precursors wlth mirilmum terrestrial resupply. The production of silane from lunar materials may require a key, lunar-produced intermedlate, magnesium silicide (Mg_2Si). Mineral acid or water terrestrial resupply will be required to produce snare by this synthesis. It appears that the propellant properties of oxygen and silane are more than adequate to support the development of a lunar-based propulsion system. Silane is stable and storable in space and lunar envlronments and has properties that are compatible with those of oxygen Using standard Aerojet-JANNAF procedures, the estimated delivered performance of the propulsion system is 340-350 s at a mixture ratio of 1.50 to 1.80 . Penalties normally associated with pressure-fed propulsion systems may be mirnmized in the lunar environment, In, 1/6 g. A pressure-fed propulsion system may prove to be quite competitlve with a pump-fed system.

INTRODUCTION

The Moon is made of oxygen That is, the Moon is rich in minerals from which oxygen can be manufactured Unfortunately, the Moon does not possess adequate, easily exploited sources of hydrogen- or carbon-containing minerals. This poses a particular problem for a designer of a lunar-based propulsion system, as an adequate supply of both oxidizer and fuel is required to power the system. One solution to the problem is to transport the required fuel from the Earth, or from low Earth orbit, to the Moon.

Hydrogen is one candidate fuel because it offers excellent performance with oxygen. Unfortunately, hydrogen has an extremely low density and is very difficult to store as a liquid. Monomethylhydrazine (CH_3N_2H3) is another candidate fuel since it offers satisfactory density, storage properties, and performance. It would, however, have to be transported from the Earth for use in a lunar-based propulsion system.

Perhaps there is a middle position in regard to the manufacture of a suitable fuel on the Moon. There may be a satisfactory fuel that can be manufactured by using lunar resources and some chemicals resupplied from the Earth, namely, silane.

LUNAR RESOURCES FOR PROPELLANT MANUFACTURE

The minerals required to manufacture oxygen on the Moon are abundantly available. Olivine [$(Mg,Fe)_2SiO_4$, pyroxene [$(Ca,Mg,Fe)SiO_3$, and ilmenite ($FeTiO_3$) are particularly attractive raw materials for lunar oxygen manufacture. The major minerals, such as olivine, pyroxene, and the plagioclase feldspars l(Ca,Na)$Al_3Si_20_3$] occur in concentrations approaching 100%. The minor minerals generally occur at concentrations *of* less than 2%; however, some, particularly ilmenite, occur at concentrations of up to 20%.

The chemistry of the lunar minerals of interest has been confirmed by the analysis of Apollo samples (Williams and jadwick 1980). In regard to lunar oxygen manufacture,

Table 1. Apollo 'sample Analyses

Compound	Mare, wt %	Highland, wt %
Analyses *of Typical Lunar Olivine*		
$5iO_5$	37.36	37.66
2	0.11	0.09
Cr_2O_3	0.20	0.15
Al_2O_3	<0.01	0.02
FeO	27.00	26.24
M80	022	032
MgO	35.80	35.76
caO	027	0.16
	<0.01	<0.01
Total	100.97	100.40
Analyses of Typical *Lunar Pyroxenes*		
'siO_2	47.84	53.53
710_2	3.46	0.90
Cr_2O_3	0.80	0.50
Al_2O_3	4.90	0.99
FeO	8.97	15.42
	0.25	0.19
MgO	14.88	26.36
cao	18.56	2.43
	0.07	0.06
Total	99.73	10039
Analyses *of Typical Lunar* Ilmenite		
	0.01	021
	53.58	54.16
Cr_2O_3	1.08	0.44
Al_2O_3	0.07	<0.01
FeO	44.88	3738
Mn0	0.40	0.46
MgO	2.04	6.56
Zr0	0.08	0.01
V_2O_2	0.01	<0.01
Na_2O	<0.01	0.13
Total	102.16	99.37

the focus is on the concentrations of silicon dioxide and iron oxide. The concentration of magnesium oxide is important for the manufacture of lunar silane. Note the comparatively high concentrations of these oxides in lunar olivine, Table I. On balance, lunar olivine appears to be the mineral of choice for the manufacture of the propellants required for a lunar-based propulsion system.

PROPELLANT MANUFACTURE FROM LUNAR RESOURCES

Ilmenite, which is essentially ferrous titanate, can be reduced directly with hydrogen to form water, iron, and titanium dioxide. Electrolysis of the water yields oxygen, the required oxidizer, and hydrogen, which is recycled in this process (Kibler *et al.,* 1984; Gibson and Knudsen, 1984).

$$2\ FeTiO_3 + 2 \qquad\qquad 2\ H_2O + 2\ Fe + 2\ Ti0_2 \tag{1}$$

$$2\ H_2O \ \underline{\text{electrolysis -> 2}}\ H_2 + 0_2 \tag{2}$$

In the ideal case, 32 g of oxygen is obtained from 320.2 g of mare ilmenite, Table 1. However, at best, only 20% of the lunar material that must be processed is ilmenite. Therefore, 1,601 g of raw material must be processed to obtain 32 g of oxygen, a yield of only 2.0%.

It is apparent that the lunar raw materlal will have to be enriched in ilmenite before hydrogen reduction, i.e., (I), to reduce the size of the chemical plant. Enrichment studies are currently being conducted (Agosto, 1984). Note, however, that while efficient enrichment reduces the size of the processing plant required for the hydrogen reduction step, it does not reduce the amount of lunar raw material that will have to be mined and transported. In the *ideal* case, 100.0 kg of mare material will have to be processed to manufacture 2.0 kg of oxygen.

The other major constituent oxides cannot be reduced directly with hydrogen to form water and the elemental metal. Silicon dioxide, as contained in olivine and pyroxene, can be reduced using the carbothermal process to form oxygen, silicon, and magnesium oxide. The ferrous oxide is reduced as well to form oxygen and iron (Rosenberg et al., 1964a,b, 1965a,b, 1985).

$$\underset{\text{olivine}}{Mg_2SiO4} + 2\ CH_4\ \underset{\text{reduction}}{\underline{\text{carbothermal ->,}}}\ 2\ CO + 4\ H_2 + Si + 2\ MgO \tag{3}$$

or

$$\underset{\text{pyroxene}}{MgSiO_3} + 2\ CH4\ \underset{\text{reduction}}{\underline{\text{carbothermal->}}}\ 2\ CO + \mathbf{4\ H_2} + Si + MgO \tag{4}$$

$$2\ CO + 6\ H_2\ \underset{\text{reduction}}{\underline{\text{catalytic,}}}\ 2\ H_2O + 2\ CH4 \tag{5}$$

$$2\,H_2O \xrightarrow{\text{electrolysis}} 2\,H_2 + O_2 \qquad (6)$$

In the ideal case, 32 g of oxygen is obtained from 123.56 g of mare olivine (see Table 1), a yield of 25.9%. Thus, 3.86 kg of olivine will have to be processed to manufacture 1.0 kg of oxygen, providing a 13-fold advantage over ilmenite in the ideal ilmenite case.

While the Moon has abundant resources for oxygen manufacture, fuel sources are scarce indeed. There are no known sources of free or bound water or carbonaceous minerals. The concentration of solar wind implanted hydrogen of approximately 50 to 200 ppm in lunar regolith (Carter, 1984; Friedlander, 1984) appears to be too low to be of practical value for large scale fuel manufacture.

Silane is an article of commerce in the United States today, as it is used in the manufacture of chips for our electronics industry. Silane is usually manufactured by a process that may prove to be too complex for lunar application, e.g., the reduction of silicon tetrachloride with lithium aluminum hydride.

It may be possible to simplify the manufacturing process while minimizing dependence on terrestrial resupply by the use of the reaction between hydrochloric acid and dimagnesium silicide (Sneed and Maynard, 1947).

$$2\,MgO \xrightarrow{\text{electrolysis}} 2\,Mg + O_2 \qquad (7)$$

lunar derived
e.g, carbothermal process

$$2\,Mg + Si \quad \underline{9} \quad Mg_2Si \qquad (8)$$

lunar
derived,
e.g, carbothermal process

$$4 \qquad (9)$$

terrestrial
resupply

In a more complex cyclic electrolysis process, it may be possible to electrolyze the magnesium chloride to form the required magnesium and hydrogen chloride, and oxygen as a byproduct. In this synthesis, water would be resupplied from Earth rather than hydrochloric acid [see also (8) and (9) above].

$$2\,MgO + 4\,HCl \rightarrow 2\,MgCl_2 + 2\,H_2O \qquad (10)$$

lunar derived

$$2\,MgCl_2 + 2\,H_2O \xrightarrow{\text{electrolysis}} 2\,Mg + 4\,HCl + O_2 \qquad (11)$$

terrestrial
resupply

The resupply of water from the Earth maybe less troublesome than that of hydrochloric acid Water transport should be a standard item in the support of permanent lunar bases. Note that the oxygen that occurs as a byproduct in the manufacture of silane, i.e., (7) and (II), can be used to support propulsion needs. The byproduct water, i.e., (10), would be put to good use as well.

The technology for the manufacture of silane from lunar resources has not been studied Process research and demonstration are required.

PROPELLANT PROPERTIES

The use of liquid oxygen is well established It is used today to power the Space Shuttle Main Engine and the Centaur Upper Stage RL-10 Engine. It will be used in the future to power propulsion systems for advanced orbit transfer vehicles, becoming an integral part of the United States Space Station (Davis, 1983a,b; Babb et *al.,* 1984).

Comparative physical property values for oxygen, silane, and methane are presented in Table 2. Note that silane has a broader liquidus range than methane, which is a great benefit to the propulsion system and rocket engine designer. Silane is hypergolic with oxygen, which is an additional benefit Methane and hydrogen are not hypergolic with oxygen This gives additional complexity to the engine system.

The propellant properties of silane have not been defined adequately. However, it appears that silane has the potential to be an adequate space storable propellant

Table 2. Physical Properties of Potential Lunar Propellants

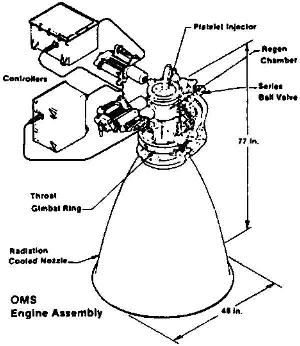
	Melting Point		Bolling Point		'specific Gravity
Propellant	°F		°F	°C	**(liquid)**
Oxygen O_2	-361	-218.4	-297	-(83	1.142(-297°F)
Silane, SiH_4	-301	-185	-169.4	-111.9	0.68(-30(°F)
Methane, CH_4	-296.7	-182.6	-258.3	-161.3	0.46(-296.7°F)

1. SiH_4 is thermally stable to cA. 800°F.
2. *$0_2/SiH4$ is* hypergolic
3. SiH_4 is **a liquid at the nbp of** O_2 .

A LUNAR-BASED PROPULSION SYSTEM

Pressure-fed liquid bipropellant engines and propulsion systems are attractive because of their comparative simplicity. Their disadvantages are lower performance and the need for heavier weight tanks and a tank pressurization system. This results in heavier propulsion systems, Le, increased propellant and hardware weights.

A pressure-fed engine in the STS Orbiter Maneuvering System Engine format seems to be appropriate for use with the $LO_2/LSiH_4$ bipropellant combination, Fig. I. This Aerojet TechSystems engine, which delivers 6,000-IbF thrust and operates with the



Engine Parameter	Actual OMS-E Value	Estimated Lunar-E Value
Thrust, lbf	6000	6000
Mixture Ratio	1.65	1.50 to 1.80
Chamber Pressure, psia	125	125 to 155
Specific Impulse, lb-sec/lb	316	345±5
Propellants	$N_2O_4/CH_3N_2H_3$	LO_2/SiH_4
Total Flowrate, lb/sec	19	17.2±0.5
Inlet Temperature, °F	40 to 100	TBD
Single Burn Duration, sec	1250*	TBD
Cumulative Firing Life, sec	54,000	TBD
Regen Exit Area Ratio	6:1	TBD
Area Ratio	55:1	TBD
Weight (dry), lbm	260 (316)	
Storage Life, yrs	10	TBD
Restarts	Unlimited	TBD
Blowdown, lbF	7,600 to 5,500	TBD
Inlet Oxid. Pressure, psia	239	TBD
Inlet Fuel Pressure, psia	242	TBD

*Limited By Tank Volume Only

Figure *I.* *The* Space Shuttle OMS-Engine *provides a* format for the lunar engine.

bipropellant combination at a mixture ratio of 1.65, has a regeneratively cooled thrust chamber. The OMS-E has a delivered specific impulse of 316 s.

If the regeneratively cooled thrust chamber can be adequately cooled with silane, and there is every reason to believe it can because of silane's thermal stability (Table 2), the development of a suitable long-life, reusable engine based on $LO2/SiH_4$ appears to be quite achievable. Such an engine should have a delivered specific impulse of approximately **345** s.

The pressure-fed propulsion system penalties associated with an Earth-launched system would have to be reassessed in the light of a Moon-launch system. In the 1/6 g environment of the Moon, the apparent disadvantages of a pressure-fed system may be less, and a pressure-fed engine system operating at a higher chamber pressure may be appropriate. Detailed analysis would have to be performed to address these and other issues associated with the selection of a pressure-fed propulsion system.

Eagle Engineering has studied the impact of lunar-produced silane upon lunar oxygen production logistics in the context of the transfer of the lunar-produced oxygen from the Moon to low Earth orbit. A comparison was made between the use of a pump-fed LO2/LH2 propulsion system (lspv 480 s, MR 6.0) and a pressure-fed LA2/LSiH, propulsion system (Isp, 345 s, MR 1.80). Lunar-produced silane was used as the fuel in the propulsion system in place of Earth-supplied hydrogen. A small gain, i.e., 2.5% in mass of oxygen transferred was derived by the substitution of silane for hydrogen. The $LO2/LSiH_4$ propulsion system offers a modest benefit despite the 135 s difference in assumed specific impulse values.

In a postscript to this report, Eagle Engineering indicated that the use of a 5.0% higher mass fraction for the stage and a 1.45% higher specific impulse for the propulsion system resulted in a 29% increase in the mass of lunar-produced oxygen delivered to orbit on each ascent (Davis, 1983b). These improvements could be attained by the development of a pump-fed LO_2 /ISiH_4 propulsion system.

Much work remains to be done to put such propulsion systems in place. However, the work required appears to be straightforward. No inventions are required to demonstrate technology readiness and enter development and production.

CONCLUSIONS

Whether or not a lunar-based propulsion system, more particularly, one based on LO2/LSiH_4 , will ever be developed will depend upon many factors that are beyond the scope of this paper. However, the technology to manufacture oxygen and silane on the Moon and also to develop a lunar-based propulsion system based on the bipropellant LO_2/LSiH_4 combination is within our reach. The development of a lunar-based propulsion system can be accomplished within the time frame under consideration, i.e., by the start of the 21st century. All that is required are the need, the will, and the funds.

Acknowledgements. *The* author wants *to* acknowledge the *support* that he received from Hubert P *Davis* *and his colleagues at Eagle* at Aerojet 7eNtSystems *in Sacramento,* California

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LAUNCHING ROCKETS AND SMALL SATELLITES FROM THE LUNAR SURFACE

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Scientific payloads and their propulsion systems optimized for launch from the lunar surface differ considerably from their counterparts for use on Earth. For spin-stabilized payloads, the preferred shape is a large diameter-to-length ratio to provide stability during the thrust phase. The rocket motor required for a 50-kg payload to reach an altitude of one lunar radius would have a mass of about 41 kg. To place spin-stabilized vehicles into low altitude circular orbits, they are first launched into an elliptical orbit with attitude about 840 Ion at aposelene. When the spacecraft crosses the desired circular orbit, small retro-rockets are fired to attain the appropriate direction and speed Values of the launch angle, velocity increments, and other parameters for circular orbits of several altitudes are tabulated To boost a 50-kg payload into a 100-km attitude circular orbit requires a total rocket motor mass of about 90 kg

INTRODUCTION

The scientific investigation made possible by the Apollo project in the 19705 led to remarkable success in defining the Moon as a solar system planetary body. The synthesis of this great quantity of geochemical and geophysical data has, among other achievements, led to a theory of the Moon's origin that is more consistent with these data than previous theories have been.

Much was learned during the Apollo days about the Moon's gravity and magnetic fields, its atmosphere, and its interaction with the solar wind. However, much has been left unknown about these important topics, due in part to the restriction of the Apollo landing sites and in-orbit investigation to a fairly small range of latitudes about the Moon's equator. A powerful new attack on unsolved lunar scientific questions would be made possible by manned bases on the Moon's surface. With such resources, sounding rockets and even small orbiting vehicles carrying scientific payloads could be brought to the Moon and launched into a variety of interesting trajectories. In this paper, we attempt to define some of the technical characteristics such vehicles would have. We illustrate the use of rockets and satellites launched from the lunar surface with a few scientific experiments that are of current interest. We recognize this study to be a highly preliminary one and that the flight of a lunar polar orbiter before manned bases are established could greatly change what scientific experiments would be done. In any case, detailed planning and selection of the scientific experiments would be a prerequisite to any such program of rocket and satellite launching from the Moon's surface.

DISCUSSION

The launching of rockets or orbiting vehicles from the Moon's surface is quite different from the launching of such vehicles from Earth's surface for the following two reasons: (I) there is no atmosphere to produce aerodynamic forces on the vehicle; (2) the surface gravity is low. The acceleration due to gravity at the Moon's surface is about $1.63\ \mathrm{m/s^2}$.

These environmental factors have several consequences to the design of the rocket motors and payloads:

(1) A nose cone to protect the payload from aerodynamic forces is not required. The advantage gained in this way is that total mass of the system is lowered. The reduction in mass results not only from absence of the nose cone but elimination of the nose cone ejection mechanism as well. For some payloads under some launch conditions,

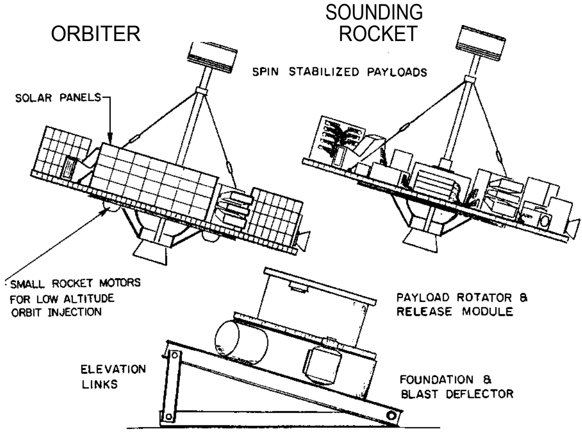

Figure 1. Possible configuration for a small scientific payload and propulsion system suitable for launch from the lunar surface. For use as an orbiting vehicle the sounding rocket must be augmented by solar panels and small rocket motors to provide a second velocity increment A 50-kg spin-stabilised payload can be put in a low altitude circular orbit by about 90 kg of rocket motors and fuel mass

protection from dust blown off the surface by the rocket motor might be necessary; then a dust cover and means of opening it would be required. However, such a device would be simpler and less massive than the nose cone and ejection mechanism used in launches from Earth's surface.

(2) The absence of aerodynamic forces means that the diameter of the payload may be made as large as desired A large diameter would result in a much simplified mechanical design and ease of assembly of the subsystem on the payload platform. For example, the added space would make layout and cabling much easier. The greater accessibility results in ease of troubleshooting and ease of replacement of subsystems or experiments. Figure 1 shows how such a payload platform might appear.

The large diameter payload has one other great advantage. The moment of inertia about the thrust axis of the vehicle, $I_{\parallel}$, could be made much larger than the moment of inertia about axes perpendicular to the thrust axis of the rocket motor, I. Thus, simple spin-stablized vehicles would have large $I_{\parallel}/I_{\perp}$ ratios, the requirement for "flywheel stability." This situation is highly desirable since there is much less tendency for large-angle precession of the thrust axis about the direction of flight Rockets with a small $I_{\parallel}/I_{\perp}$ ratio, the condition for most Earth-launched rockets, have a tendency to go into a flat precessional motion rather than remaining nose up.

(3) The low gravitational force on the Moon's surface greatly reduces the total impulse requirement in order to achieve a given peak altitude or to attain low altitude orbital speed. In the case of chemical rocket motors, this means that the mass of the motor plus fuel is greatly reduced compared to the terrestrial situation. A further significant mass reduction follows from the absence of atmospheric drag. Because there is no need to keep the cross section of the vehicle small, the motors may be made spherical, thereby attaining a more favorable fuel-to-total-motor-mass ratio than is attainable from thin, cylindrical motors. Table I gives specifications of two rocket motors, one that will take a 50-kg payload to altitude of 100 km and the other will take the same payload to an altitude of 1738 km (one lunar radius). The term payload includes everything on the vehicle except the motor and its fuel.

An interesting scientific use of a sounding rocket capable of taking a plasma, particle, and field diagnostic payload to an altitude of 1738 km above the Moon's surface is indicated

Table 1. Specifications of Solid Fuel Rocket Motors Suitable for Launching Small Scientific Payloads From the Lunar Surface

	Length	Diameter	Mass at Ignition	Propellant Weight	Mass of Empty Motor
Motor A	29.4 cm	19.6 cm	13.9 kg	11.1 kg	2.8 kg
Motor S	50.5 cm	33.7 cm	41.1 kg	32.9 kg	8.2 kg

Motor A will take a 50-kg payload to an altitude of 100 km above the Moon's surface: Motor B will take the same payload to an altitude of one lunar radius (1738 km). The specific impulse of the propellant was taken to be 296 s.

in Fig. 2. When the Moon is in the solar wind, a void is formed behind it, and an expansion fan forms to fill the void. A limb shock is likely to be present, and the void and expansion fan can be expected to have interesting physical properties as well. The rocket just mentioned above would be able to sample all these regimes and their boundaries and provide a detailed description of the boundary layer and shock structure. Figure 3 indicates where these boundaries would appear on the rocket trajectory for typical solar wind conditions and for two different launch latitudes, the equator and 45°.

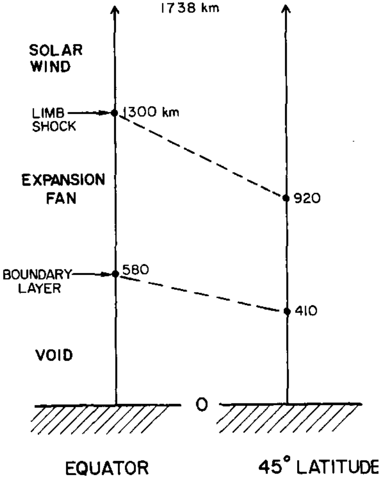

Figure 2. A sounding rocket launched vertically upward from the Moon's surface would encounter several distinctive regimes in the interaction of the solar wind with the Moon. The void expansion fan, and solar wind would all be sampled as would two thin structures the boundary layer between the void and expansion fan, and the limb shock

We have also briefly considered the use of electromagnetic launchers (EML) to inject scientific payloads into a variety of trajectories from the lunar surface. There are several disadvantages to this method For example, the acceleration a required to attain low altitude orbital speed of 1.686 km/s is given by

$$a = \frac{1.41 \times 10^{6}}{S}\ \mathrm{m/s^2} \tag{1}$$

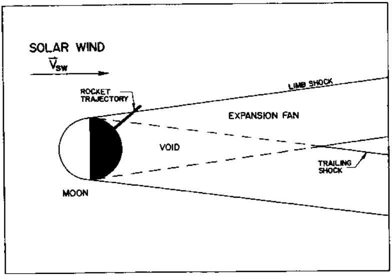

Figure 3. *Altitudes at which the different features of* the *solar wind interaction* with the *Moon* would appear *during the rocket flight shown in Fig 2.* The *peak altitude of the rocket is one* lunar *radius, its flight time about 45 minutes TO* achieve this *trajectory, a payload of 50 km* requires *a rocket motor plus fuel mass of about 41 kg*

where S is the length of the EML Even a launcher 100 m in length would subject the payload to an acceleration of 14,100 m/s2 or 1439 times Earth's gravitational acceleration. While scientific payloads might be designed to withstand such acceleration, it would be more expensive to do so. Another disadvantage of the EML is that almost certainly magnetometers would become severely contaminated by the very large magnetic fields generated by this type of launcher. Finally, an EML dedicated to launching scientific payloads would be more expensive than launch set-ups for chemically propelled vehicles (see Fig. t). This is especially true if a variety of launch locations, azimuths, and elevations are desired.

We have also investigated launch of spin-stabilized spacecraft utilizing solid fuel motors into circular orbits of specified altitude without reorientation of the spin axis (i.e, the spin axis remains inertially fixed during the injection sequence). Of course, attitude control systems could be used, but these add mass to the vehicle and increase the cost Circular orbits can be achieved from vehicles initially at rest on the Moon's surface by using two velocity increments. The simple launch platform used for sounding rocket launchers could also be used for launch into circular orbits (Fig. 1). The first event in the launch sequence is to set the azimuth and elevation angles of the platform. Azimuth would be determined by experiment requirements. The elevation angle required to achieve a circular orbit of desired altitude is calculated by a method described below. For circular orbit altitudes in the range 50-100 km, the angle is about 3.5°. The spacecraft is then placed in the platform and spun up. The main motor is ignited and burns for about 11 seconds. A speed close to the desired low altitude circular orbit speed is reached at burnout This velocity increment, dV„ is about 1830 m/s. At burnout of the main motor, the spacecraft is approximately 8 km downrange at an altitude of 0.4 km. The second velocity increment, dV2, is applied where the elliptical orbit crosses the desired circular orbit after aposelene. We have found values of dV, that result in nearly circular orbits of 50-100 km altitude. This sequence of events is illustrated schematically in Fig. 4.

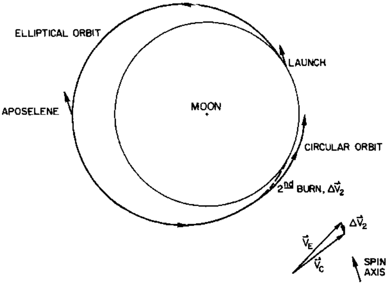

Figure *4. Illustration of* the *injection sequence of* a *spin-*stabilized spacecraft into a *orbit about* the *Moon.* The spin *remains inertially fixed* over *the elliptical trajectory. Orbit altitude is* controlled *mainly* try *the time to* second burn. V_E is *the orbit* velocity *just prior to the second burn;* Vc is *the* resultant *circular orbit* velocity. *The* second *velocity* increment *is much smaller than* the first one

Table 2 gives the launch angle and velocity increment necessary to achieve circular orbits for several altitudes. The second velocity increment can be achieved by small rocket motors whose thrust is directed opposite to the main motor. There is little advantage to jettisoning the main motor after burnout since its mass is so small. The mass of the small motors needed to provided the dV_2 would be less than 10 kg. Ignition of the small motors would be accomplished by a timer set to close the firing circuits a preset time after launch. These times are also given in Table 2.

A computer program tests Keplerian ellipses that intersect the Moon's surface and cross the desired circular orbit. The spin axis of the rocket, fixed at launch, is tangent to the ellipse where it enters the Moon. A velocity increment is made when the ellipse crosses the desired orbit. This increment is calculated to change the direction of motion to that of a circular orbit If this increment results in the proper speed, as well, the computer prints the appropriate data. If not, another ellipse is tested. For the examples in the Table, the original eccentricity was arbitrarily fixed at $t = 0.20000$, and the aposelenes were all about 840 km. The launch angles for these ellipses are about 3.5° above the local

Table 2 Injection Parameters for Low Altitude Circular Orbits About the Moon

Nominal Orbit	Launch Angle, y			Time to Injection	Final Orbit T max	 T min	 Eccentricity
50 km	3.6°	1835.0 m/s	-233.9 Ms	137.10 min	61.2	48.4 km	0.00356
75 km	3.5°	1835.6 m/s	-249.0 m/s	1 29.51 min	86.4 km	72.8 km	0.00374
100 km	3.2°	1836.6 m/s	-261.1 m/s	128.37 min	(00.3 km	98.9 km	9.00035

A payload mass of 50 kg is assumed

horizontal drection. Shallow launch angles would present difficulties only for launch sites near lunar mountains. Circular orbit insertion would take place about 310° around the Moon from launch and requires thrust from small motors drected opposite to the main motor (see Fig. 1).

The rocket will travel 8.3 km during the 11 s primary burn, but lunar gravity will deflect it into a slightly different ellipse than that calculated above. The velocity and altitude at main motor burnout are used to determine the length of the major axis of the new ellipse. The eccentricity and orientation of the major axis are determined numerically.

The most important difference between the original ellipse and the actual trajectory is the time the rocket crosses the circular orbit. The time between launch and orbit crossing ls found by numerical inversion of Kepler's equation. Errors introduced by neglecting the duration of the second bum (2 seconds) are negligible. The unadjusted angle and magnitude of the velocity increment are not far from the ideal, and the final orbit is nearly circular.

Accuracies better than those obtained here are quite possible, and the quality of the orbit may be limited only by rocket motor performance and perturbations due to lunar gravity anomalies. If the required tolerances for the total impulse of the primary motor cannot be assured, the second bum could be initiated by radar altimeter, accelerometer, or Moon-based tracking.

We have not carried out analyses of the dispersion of the orbit altitude achieved because this depends on a detailed system design and engineering analysis. Nor have we attempted to determine the orbit parameters and launch times that will maximize the lifetime of near-circular low-altitude orbits.

For spacecraft having orbit lifetimes of weeks or months, a solar-cell power source would be required, as well as a set of batteries to operate the system throughout the shadow interval. Since the spacecraft is spinning, the solar cells should be mounted vertically on the periphery of the experiment platform (see Fig. 1). The angle, B, that the solar rays make with respect to a vertical line drawn from the solar cell surface is given by

B=| lambda - gamma | (2)

where lambda is the latitude of the launch site. For launch sites in the latitude range 20-30°, the sun's rays lie close to the equator for the spacecraft. When the launch site for polar orbiting spacecraft is the Northern hemisphere, the launch direction should be toward the north; from Southern hemisphere bases, the launches are toward the south.

CONCLUSION

We conclude with a brief list of scientific investigations that could be carried out from low altitude lunar circular orbits

(1) A low altitude polar orbit would permit a global survey of the Moon's small scale magnetic fields by both flux gate magnetometry (Russell *et al.,* 1975) and electron reflection magnetometty (Howe *et al.,* 1974; Anderson *et al.,* 1977). Field strengths at

the surface of only 3 x I0' Gauss (0.03 nT) and scale sizes of a few hundred meters or less could be determined The flux gate magnetometry will provide accurate directional informatlon on the more extended magnetic fields and the electron reflectance can provide some information on direction. When combined, the two methods of magnetometry can also yield information on the size and depth of the magnetized lunar rock One goal of such studies is to determine if the Moon once possessed an active dynamo (Runcom, 1978) and if not, to determine the probable cause of the ancient magnetic fields. Another objective is to correlate magnetic features with surface geological features.

(2) The small scale features of the Moon's gravity field, including mascons, could be determined by tracking the low altitude orbiter (Sjogren et *of,* 1974). Transmitters suitable for this purpose, and of sufficient power to be received by Earth stations, could be included on low altitude orbiter flights,

Acknowledgments *We* thank the Advanced *Projects* Group *of* Bristol *Aerospace Ltmited W/nm* prg. *Conde* for design information *on solid* fuel rocket motors The *work at* Berkeley was supported by *NASA* Grant NGL *05-003-017*

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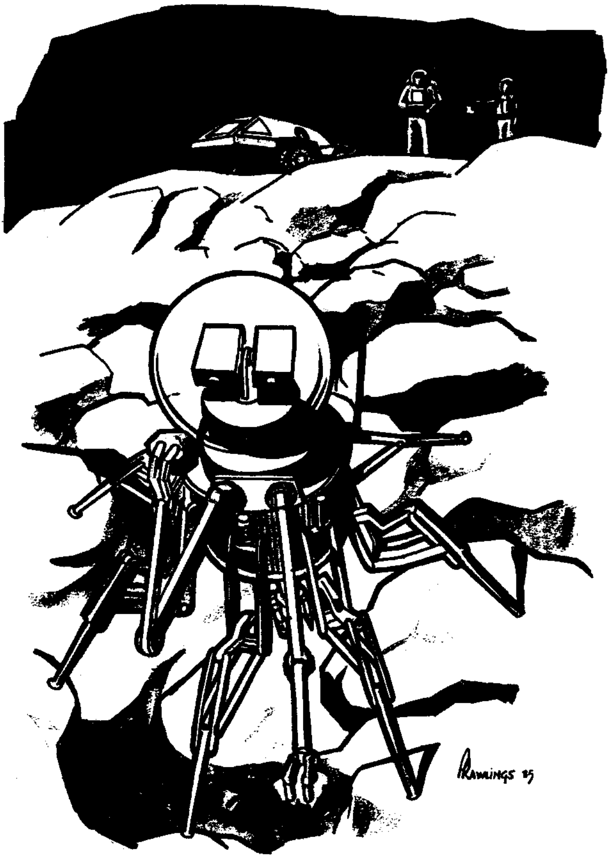

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DREAMS AND REALITIES: THE FUTURE IN SPACE

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What factors must converge to create a societal commitment to creating a permanent human base on the Moon? There have been three major decisions to start manned space programs in the past 25 years—those which began Apollo, the space shuttle, and the space station An examlation of these decisions suggests that no one particular sltuation facilitates major commitments rather, a commitment results from the convergence of the poltical context the goals of political leaders, particularly the President the needs of various space institutions, particularly NASA; the success of earlier programs and the options available at a particular decision point While many of these factors are beyond the control of advocates of a hear base, there are a variety of steps that can be taken over the next *few* years to improve the chances of program approval at some future time. However, advocates of a hoar base should recognize that it is unlikely that the political leadership will be willng to support another major space program until the space station is nearing operationat status sometime in the 1990.

INTRODUCTION

It is argued that "when the requisite technology exists, the US. political process inevitably will include lunar surface activities" (Duke AS *al.,* 1985, p. 50). To a student of the political process, such an assertion of inevitability must be viewed with some skepticism, especially when it seems linked primartly to the existence of "requisite technology." It is important for those who want to see a "return to the Moon" goal accepted as an important aspect of future US. space policy to recognize that, while developing the requisite technology is a necessary condition for a lunar base program, it is far from a sufficient one.

What factors are essential for creating a political commitment to a lunar base? It is impossible to forecast, at least in specific terms. The United States government has, in the past three decades, initiated three major manned space programs—Apollo, space shuttle, and space station; thus it certainly is not impossible to organize and sustain a political commitment to a multi-year, multi-billion dollar enterprise in space, even though such politically supported undertakings are the exception rather than the rule in the United States. Initially, this paper explores these three decisions in order to identify their major characteristics; then, these characteristics wlll be compared in order to make some useful general comments on the conditions that might lead to the hoped-for commitment to a lunar base program at some future date.

Apollo as a Crisis Decision

In times of crisis—situations that allow only a short time for response without extensive prior planning and where the issues at stake are of great importance—many of the barriers to rational, "top-down" decision-making disappear. Such a situation occurred in April, 1961 (Logsdon, 1970). The self-image and international standing of the United States had been stung in rapid succession by the surceov of the Soviet Union in orbiting the first man, and by the failure of the United States to follow through in support of the invasion of Cuba by U.S.-trained forces at the Bay of Pigs. In a memorandum dated April 20, 1961, President John F. Kennedy asked:

> Do we have a chance of beating the Soviets by putting a laboratory in space or by a trip around the moon or by a rocket to land on the moon, or by a rocket to go to the moon and back with a man? is there any other space program which promises dramatic results in which we could win?

What Kennedy hoped was to demonstrate to the world, through space achievements, that the United States remained the leading nation in technological and social vitality. Almost equally important, though not as clearly articulated, Kennedy saw such achievements as a means of restoring American pride and self-confidence. The Soviet Union's surprising demonstration of technological and strategic strength through its series of space firsts leading to Yuri Gagarin's flight had shaken our image of the United States as the unchallenged technological leader of the world.

After two weeks of assessing alternative answers to these questions, Kennedy's advisers, led by Vice-President Lyndon Johnson, agreed that the United States had at least a fifty-fifty chance of winning a competition to complete a successful manned lunar expedition and that no other alternative provided a better combination of achievement, risk, and cost Kennedy accepted this assessment, and the Apollo program was born.

The memorandum to the President recommending the lunar landing effort was signed by Johnson, NASA Adminstrator James Webb, and Secretary of Defense Robert McNamara. It stated clearly the rationale underpinning the enterprise:

> it is man, not merely machines, in space that captures the imagination of the world. All large-scale projects require the mobilization of resources on a national scale. They require the development and successful application of the most advanced technologies Dramatic achievements in space therefore symbolize the technological power and organizing capacity of a nation. It is for reasons such as these that major achievements in space contribute to national prestige.

Space achievements developed prestige, they asserted, in the power struggle between the United States and the Soviet Union; the United States should thus undertake a manned mission to the Moon, even if the scientific or military grounds were lacking:

> Major successes, such as orbiting a man as the Soviets have just done, lend national prestige even though the scientific, commercial, or military value of the undertaking may by ordinary standards be marginal or economicaly unjustified.... Our attainments are a major element in the international competition between the Soviet system and our own. The non-military, non-commercial, non-scientific but "ciu'tian' projects such as lunar and planetary exploration are, in this sense, part of the battle along the fluid front of the cold war.

Kennedy accepted these arguments. In announcing this decision on May 25, 1961, he told the Congress and the nation:

> *If we are to win the battle that is going on around the world between friends and tyranny, If we are to win the battle for men's minds the dramatic achievements in space which occurred in receru weeks should have made clear to us all, as did the Sputnik in 1957, the impact of this adventure on the minds of men everywhere who are attempting to make a determinatlon of which mad they should take ... We go into space because whatever mankind must undertakefree men must fitl3r share.*

Apollo emerged from a crisis atmosphere, and stands as a powerful example of the fact that government can make and can keep a commitment to multibillion-dollar, long-term programs when they serve broad national purposes and are begun with adequate political support. The existence of a crisis situation made the Apollo commitment possible; it did not make it inevitable. Other circumstances had to converge to make Apollo happen. They include:

1. Enough prior research to assure decisionmakers that the proposed undertaking was technologically feasible; a manned lunar mission had been under serious examination for several years prior to the Kennedy decision, and no technological obstacles had been identified. NASA had selected a lunar landing as the appropriate long-term objective of its manned flight program over a year before May, 1961.
2. The undertaking was the subject of enough political debate that groups interested in it and opposed to it were identified and their positions and relative strengths were evaluated, and potential sources of support had time to develop. Both Lyndon Johnson and James Webb had effective working relationships with the leaders of Congress, and obtained pledges of support for an accelerated space program. The President and Vice-President also consulted non-governmental leaders to test their reaction to a vigorous U.S. response to the Soviet challenge in space.
3. In the political system, there were individuals in leadership positions whose personalities and visions supported the initiation of large-scale government activities aimed at long-term payoffs and who had the political skill to choose the situation in which such activities could begin with a good chance of success.

When Kennedy announced his decision to go to the Moon in May, 1961, there were no significant negative reactions, and the funds required to accelerate NASA's program passed Congress quickly and with little opposition. The program was well underway before such opposition first developed in 1963.

The Shuttle: a Bad Bargain?

Apollo, as a crisis decision, was an exception to how policy choices are usually made in the United States. The normal process of policy-making involves a wide variety of participants; it is characterized by bargaining among players positioned within various government organizations. Individuals and groups outside government participate in this process and can be very influential, but their power lies primarily in influencing those within the government who control the resources required to undertake a new course of action. Decisions are almost always made, not by one central decisionmaker, but by a process of interaction among various government organizations and individual political actors. The process leading to the 1972 decision to begin the space shuttle program is an example of the normal policy process in operation (Logsdon, 1979a,b).

In the shuttle decision, major participants were:

- NASA, both as an engineering organization eager to take on a new and challenging technology development job after Apollo and as a government agency interested in maintaining its budget, institutional base, and status;
- Department of Defense, attracted by the potentials of the proposed shuttle for various national security missions in space;
- the aerospace industry, interested in undertaking another major effort along the lines of Apollo;
- the Congress, still supportive of space but unwilling to approve another Apollo-like project aimed at, for example, manned planetary exploration;
- scientists skeptical of the value of or need for another major manned program to follow Apollo;
- analysts who, for the first time, examined a major space initiative in terms of its cost effectiveness;
- the Office of Management and Budget, protective of the budget and unconvinced that the shuttle was a good investment of public funds;
- the President's Science Advlsor and his supporting staff and advisory committees, who believed that some sort of shuttle program was an appropriate post-Apollo space initiative, but who were skeptical of the NASA-defined shuttle as being the best approach to lowering the cost and increasing the ease of access to space;
- President Nixon and his policy advisers, skeptical of the future political payoffs from major space programs but unwilling to take the United States out of manned space flight and concerned about the employment impacts of programs such as the shuttle in key electoral areas like California.

The shuttle decision was the end product of a high-pressure, broadly-based, sometimes confusing debate that extended from early 1969 to early 1972, reaching a peak in the second half of 1971. The shuttle that President Nixon finally approved for development was dramatically different in both design and estimated cost from that which NASA had originally hoped to develop. NASA's planned shuttle had been part of a grand design for the post-Apollo space program aimed ultimately at a manned mission to Mars, with a space station and a lunar base as intermediate goals. The final shuttle design emerged from a process of negotiation, compromise, and conflict; it had the rationale, technical characteristics, and cost implications required to gain the support of the President and his advisers, the Department of Defense, and a majority of Congress, while still meeting most of the needs of NASA and its contractors. This coalition was able to overcome continuing opposition from the scientific community and the President's budget office, and thus provided enough support for the program to gain approval.

It was barely enough support, however, and the compromises made to make the decision politically acceptable made program success difficult to attain. NASA agreed to tightly constrained annual and total budget ceilings for the shuttle program, with little flexibility to accommodate technical problems that might arise. Some aspects of shuttle design may have been underexamined in the rush to make a decision, and NASA may have been overly optimistic in assessing the risks and technological readiness of various elements of the shuttle program, particularly the main engines and thermal protection system.

Further, what political support the program had (beyond NASA and its contractors) was not very intense. Only a few in the Department of Defense were involved in the decision process; the bulk of the Air Force was unenthusiastic. Presidential support was neither active nor strong, as had been the case with Apollo. Neither the President nor Congress had accepted, at the time of the decision, a vision of the nation's objectives in space that gave purpose and priority to the shuttle program. Not until the shuttle was threatened with cancellation in 1979 did the top leaders of the country decide it was critical to the verification of the proposed strategic arms limitation agreement (SALT II) and thus deserving of the support required to make it successful.

Selling the Space Station

NASA was forced in 1972 to accept a scaled-down shuttle program as all that it could "sell" to the nation, given the political context of the time. As shuttle development neared completion, the incoming NASA leadership in mid-1981 identified a permanently-manned space station as the agency's top choice for its post-shuttle program. Two and a half years later, after an intensive coalition-building effort, NASA was able to obtain approval to begin station development. Thus the decision to build the space station was another product of normal, non-crisis policy-making, but this time the President was active and supportive, and in the end that support proved decisive in allowing NASA to proceed with its top priority program (Waldrop, 1984).

Major participants in the space station decision were:

- NASA, needing another major development program to keep its technical capabilities fully occupied;

- the aerospace industry, hoping to continue to receive major NASA contracts but also beneficiaries of a major defense buildup;
- the Congress, which had been pushing for several years for a statement of long-range goals in space;
- the scientific community, determined to oppose any large new NASA program that would compete with space science missions for resources;
- the Office of Management and Budget, more convinced than ever that major manned space programs were an unneeded drain on the federal budget;
- the Department of Defense and other elements of the national security community, which opposed the space station both because it was not essential to any military need and because it might compete with higher priority DOD programs for funding;
- an emerging community of potential space station users and organizations committed to developing commercial applications of space technology;
- President Reagan and his policy advisers, who saw space leadership as important both symbolically and economically and who accepted NASA's argument that the space station was the logical next step in maintaining that leadership.

NASA had been studying various types of space stations for two decades prior to 1981; these study efforts were coalesced into an agency-wide task force in May, 1982. This task force identified mission requirements, assessed technological requirements, and defined a space station architecture; thus various technological uncertainties were being reduced as the decision process proceeded. NASA also asked the National Academies of Sciences and Engineering to assess the station's potential.

Thus when the station decision came before the President, the technical, policy, and budgetary aspects of the undertaking had been fully articulated, and all interested parties had had an opportunity to make their views known The President could apply his judgment in order to resolve the conflicts between NASA's proposal and the views of other agencies. He did so in a way that linked the space station to broad national objectives such as national pride, international leadership, and economic growth. Even in the face of growing budget deficits, Ronald Reagan was willing to use his Presidential prestige in support of the space station.

Whether such strong Presidential support has created a political base for the station program solid enough to withstand criticisms and attacks is yet to be seen, although the first year budget for the station program was approved essentially unchanged Just as it had taken several years to develop the support that led to a Presidential go-ahead in January, 1984, it may take several years to assess the lasting power of that support.

Some Observations

Perhaps the most basic comment to be made regarding these brief case studies is that they demonstrate how a major space commitment can emerge from three very different situations. Of the ingredients for program approval (at least in a form facilitating program success), only one appears essential: strong support from the President. Jt is basically impossible to begin and complete a large-scale, long-term government program without a lasting bankable commitment from the White House.

The word "bankable" is important here. While it is conceivable that President Reagan, acting upon the recommendations of the National Commission on Space, could announce before 1989 a commitment in principle to a long-range plan for space exploration that includes establishing a lunar base, that commitment would have limited significance until it is translated into the resources required to implement the program.

The fact that there was approximately a decade between the Apollo and shuttle and between the shuttle and station commitments suggests that the President and the rest of the policy system are likely to be willing to provide substantial funding for only one major manned space project at any particular time. While the priority assigned to the multi-billion dollar space program among various government programs has been both high and low, it is hard to imagine the President ever according the civilian space program enough priority to accommodate two or more simultaneous large development efforts. If this conclusion is valid, then lunar base advocates are likely to have to wait until the 1992-1995 period, when station funding and personnel requirements decrease and when the success of the station program is evident, before they have much hope of receiving the kind of Presidential support that commits substantial resources to their favored program.

An earlier Presidential commitment in prlnciple to a lunar base program would, of course, significantly increase the odds of a second, more meaningful commitment later. But it does not guarantee such a commitment. Decisions to begin a large-scale program are very much a product of the favorable convergence, at a particular time, of a number of factors, including:

- the specific political context;
- the visions, values, and styles of individuals in key leadership positions, particularly the President;
- the ambitions and needs of the organization that would carry out a proposed program, particularly as interpreted by the leaders of that organization;
- the ambitions and needs of other organizations that view themselves in competition for the same share of limited national resources required to carry out the program under consideration;

- the outcome of earlier programs of the same character; program success not only in technical terms but also in political terms is essential to approval of any logical next step;"
- the program choices available, their technical, budgetary, and political characteristics, and their potential payoffs.

The preceding historical review suggests how the interplay among these factors in 1961, 1969-72, and 1981-84 led to decisions to allocate substantial resources to major new undertakings in space. In retrospect, it is clear that many of the factors that made those decisions possible were well beyond the control of those advocating a major new start in space, and so it is likely to be at the time when a lunar base proposal appears on the White House and Congressional agendas.

To say that advocates of a lunar base (or any other large scale program requiring government funding) cannot control the policy process determining the program's fate is not to say that they have no influence on policy-making. There are two general categories of actions that can have such influence: (l) providing a sound technical basis for decision-makers; and (2) developing and honing a convincing program rationale and attempting to broaden the base of those who accept that rationale and are willing to advocate it.

Effective studies and preliminary research and development activities can combine both "technical" and "advocacy" components. A major role of conceptual studies and exploratory research is to reduce technical uncertainties about the character and consequences of proposed courses of action. All participants in policy-making want to understand the payoffs, the cost, and the risks associated with proposed actions, and technical studies can reduce uncertainties about such outcomes. Studies can cast light on the technical, economic, organizational, legal, and perhaps even the political consequences of a particular program, and thereby help policy-makers understand the stakes involved in their actions.

Another way technical studies can make a general contribution to policy choice is by providing the basis for an extremely persuasive argument in support of a particular course of action. If one participant in policy-making has an articulate case in support of his point of view (note that this is different from having an objectively conclusive analysis), he has a powerful asset in the policy-making process. Policy-making is not only a competition among powerful groups; some ideas and concepts also confer power on those who put them forward. In making policy in technology-intensive areas, arguments cloaked in the garb of technical analysis have particular potency.

These comments are intended to suggest an agenda for those who are convinced that a lunar base program is in the national, indeed the world's, interest While they wait with, hopefully, controlled impatience for the time, some years in the future, when a Presidential go-ahead on such a program is at least potentially attainable, program advocates should be attempting to convince those who control the relevant year-by-year budgets to provide enough support to carry out the studies and exploratory research needed to reduce those unknowns that can be explored without a major investment of resources. They should use their technical work as the basis for building a case for a lunar base that, for the time being, does not claim more than can be demonstrated rather conclusively, i.e., their advocacy should not outrun their data. They should continue to communicate their ideas to a broader audience, but not attempt to mobilize broad-scale support until it can count in policy-making.

This is a recommendation for moderation in advocacy, and is not likely to be palatable to those who want to move ahead as quickly as possible. It derives from several decades of careful observation of how the policy process works. As long as government funding continues to be absolutely required for enterprises like the lunar base, then persons interested in seeing those enterprises come into being must accept the reality of government decision-making. Wishing away the normal policy process won't work, at least in the absence of some significant action-forcing stimulus—a crisis.

In describing the decision to go to the Moon, I suggested that "the politics of the moment had become linked to the dreams of centuries and the aspirations of the nation" (Logsdon, 1970, p. 130). There is no *way* to *make* this happen, but it seems to be the necessary condition for making the dream of a permanent lunar base become a reality.

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