The initial lunar supply base should have a mass less than 1000 tons, be deployed by 25 persons in 4 months, and be maintained by 10 persons. Output could be expanded 20 times in 5 years to 600,000 tons/yr by a factor of 10 expansion of the area of the solar array on the lunar surface, using low power soil beneficiation, increasing the fleet of mining vehicles, and illuminating the base continuously at night with lunar orbiting mirrors. The space manufacturing facility (SMF) will supply most of the mass (solar cells and orbiting mirrors) necessary for expansion. Several devices and procedures are suggested for development which could further reduce the total mass necessary to transport to the Moon to establish the initial lunar supply base.

INTRODUCTION

The ultimate objective of space industrialization is to create a growing economy in space which can eventually become self-sufficient. Space industry is presently supported by sales of goods with extremely high intrinsic values, such as satellites for communications, research, navigation and reconnaissance. Low-volume production of exotic goods in the zero-gravity and weightless conditions afforded in near-Earth space may broaden the market for space produced goods. However, in all these cases the cost of transporting the goods or raw materials into low-Earth orbit will add $200-$700/kg to the product price for a period of 15 years and thus place a sharp limit on the ultimate terrestrial market (ref. 1). There appears to be a way of circumventing the present high cost of launching materials from the Earth into space. This can be done by acquiring bulk raw materials from the Moon or asteroids and processing them in space into economically valuable products. Initial bulk material costs could be of the order of $25/kg in high-Earth orbit (Salkeld, p. 187) and the cost would drop with experience. There would be two effects of lower material costs. First, the space economy could begin approaching the richness and cost structures of our present terrestrial economy. Secondly, the range of space products that could be sold for terrestrially-related use either in space or on Earth would be greatly expanded.

The Moon can supply most of the mass needed for large-scale industry in space. There are two ways to approach the proof of this statement. The first is to look in detail at the materials needed to construct specific products in space. At this point in time the production of space solar power stations is an attractive candidate because of the high value per unit mass of such objects and because of the large number of stations which could be required (>200 in next 30 years). Analyses even of designs not optimized for lunar elements reveal that at least 60 percent of the required silicon, aluminum and oxygen could be obtained from the Moon and the total mass lifted from Earth could be reduced about 80 percent by utilizing lunar materials (refs. 2, 3).

Alternatively, one can compare the nonfuel distribution of nonrecoverable elements (weight fraction) utilized in the industrial economy of the United States with elements present in the lunar soil as is shown in table 1 (ref. 4). The fraction of these elements which can be extracted with reasonable and presently available chemical processing techniques from beneficiated lunar ores is the subject of two companion papers by Williams et al. and Rao et al. (p. 275 and p. 257, respectively) discuss extraction of Si, O, Fe, Al, Ti, and H\textsubscript{2}O. Using these and other proposed extraction procedures most of the components of the synthetic molecule of "Demandite" (defined in table 1), which constitute most of the nonfuel material inputs to American industry, could be
TABLE 1.— NONFUEL DEMANDITE (U.S., 1958) COMPARED TO ELEMENTARY DISTRIBUTIONS OF SOIL AT THE APOLLO-15 LANDING SITE (WEIGHT FRACTIONS)

<table>
<thead>
<tr>
<th></th>
<th>Nonfuel demandite&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Apollo 15 mare-low Ti</th>
<th>Enhancement required</th>
<th>Bulk soil (1 unit)&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Excess</td>
</tr>
<tr>
<td>Si</td>
<td>0.2444</td>
<td>0.2158</td>
<td>1.13</td>
<td>...</td>
</tr>
<tr>
<td>O</td>
<td>.4547</td>
<td>.4130</td>
<td>1.10</td>
<td>...</td>
</tr>
<tr>
<td>Fe</td>
<td>.0479</td>
<td>.1535</td>
<td>.31</td>
<td>.01056</td>
</tr>
<tr>
<td>Al</td>
<td>.0023</td>
<td>.0546</td>
<td>.04</td>
<td>.0523</td>
</tr>
<tr>
<td>Mg</td>
<td>.0017</td>
<td>.0681</td>
<td>.025</td>
<td>.0664</td>
</tr>
<tr>
<td>(Cu,Zn,Pb)</td>
<td>.0020</td>
<td>2.2(-5)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>90</td>
<td>...</td>
</tr>
<tr>
<td>Σ&lt;sup&gt;d&lt;/sup&gt;</td>
<td>.0030 Σ - .0569</td>
<td>.0189 Σ - .2951</td>
<td>.15</td>
<td>.0159</td>
</tr>
<tr>
<td>Ca&lt;sup&gt;e&lt;/sup&gt;</td>
<td>.1417</td>
<td>.0696</td>
<td>2.0</td>
<td>...</td>
</tr>
<tr>
<td>Na</td>
<td>.0095</td>
<td>.0023</td>
<td>4.1</td>
<td>...</td>
</tr>
<tr>
<td>S</td>
<td>.0058</td>
<td>.0006</td>
<td>9.7</td>
<td>...</td>
</tr>
<tr>
<td>K&lt;sup&gt;f&lt;/sup&gt;</td>
<td>.0021</td>
<td>.0008</td>
<td>2.6</td>
<td>...</td>
</tr>
<tr>
<td>P&lt;sup&gt;e&lt;/sup&gt;</td>
<td>.0019</td>
<td>.0005</td>
<td>3.8</td>
<td>...</td>
</tr>
<tr>
<td>Cl</td>
<td>.0147</td>
<td>7.6 (-6)</td>
<td>1934</td>
<td>...</td>
</tr>
<tr>
<td>N&lt;sup&gt;e&lt;/sup&gt;</td>
<td>.0083</td>
<td>8 (-5)</td>
<td>103</td>
<td>...</td>
</tr>
<tr>
<td>C&lt;sup&gt;f&lt;/sup&gt;</td>
<td>.0574</td>
<td>9.5 (-5)</td>
<td>604</td>
<td>...</td>
</tr>
<tr>
<td>H&lt;sup&gt;f&lt;/sup&gt;</td>
<td>.0025</td>
<td>6.4 (-5)</td>
<td>350</td>
<td>...</td>
</tr>
<tr>
<td>Other&lt;sup&gt;g&lt;/sup&gt;</td>
<td>.0001</td>
<td>.0023</td>
<td>.03</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>1.0000</td>
<td>1.0000</td>
<td>(+) 0.2424</td>
<td>(-) 0.2423</td>
</tr>
</tbody>
</table>

<sup>a</sup>Demandite data supplied in reference 4.
<sup>b</sup>Formula = (Wt. fraction lunar element) - (Wt. fraction demandite).
<sup>c</sup>(N) = 10<sup>N</sup>.
<sup>d</sup>X~ Mn, Ti, Cr, Ba, F, Ni, Ar, Sn, Br, Zr.
<sup>e</sup>Important agriculturally.
<sup>f</sup>Concentrated in the smaller grains ( <50µ).
<sup>g</sup>Virtually the complete suite of elements is present in these areas, but their contributions (on the ppm and ppb levels) are lost in the errors of the sum over the listed elements. Trace element concentrations may vary greatly from one site to another.

provided in deep space at less cost per unit mass than the launch cost of the complete suite of the constituent elements directly from Earth in large tonnages until the mid-1990's (ref. 4).

Notice in column 4 of table 1 that the major demandite components (Si, O, Fe, Al, Mg, X, Ca, Na, K, P, and S) are present either in adequate concentrations or in enrichments that are 10 times the specific fractions of the soil. Beneficiation of soil components to enhance and possibly simplify known chemical extraction processes should be achievable using electrostatic, magnetic, dielectric and mechanical techniques and careful site selection. Elements such as Cu, Zn, Pb, H, Cl, N, C, and other trace elements comprise 8.4 percent of the demandite molecule. These elements would be shipped from Earth, eventually located from other sources, such as non-Apollo sites, or other materials substituted for them. In any event, it is clear that of order of 90 percent of the present day inventory of industrial elements can be provided from known lunar soils. Lunar soil processed to provide 90 percent of the demandite complement at $20/kg (i.e., Si, Al, Fe, Mg, Ca, and O) and the remainder supplied from Earth at $300/kg would provide the in-space demandite molecule at a cost of about $50/kg or 17 percent of the direct supply cost (ref. 4).
It is very clear, however, that substitution of materials, which is being required in the terrestrial economy even now, will permit much greater use of lunar materials both in general and for specific products (ref. 5). Thus, the cost of space “demandite” should approach the cost of the lunar processed materials.

The economic value to Earth of the Moon or the asteroids as a source of raw materials is strongly dependent on the total retrieval and elemental separation costs of the raw materials. Figure 1 is a qualitative description of the costs of goods or end-use-material on a dollar per kilogram basis (horizontal axis) versus the differential output of the total value of goods in the U.S. economy in billions of dollars per dollar per kilogram or \( \Delta 10^9 \$/(\$/kg) \) for a total GNP of $10^{12}$ (ref. 1).

Most goods now sell for less than $10/kg with most between $0.1/kg and $2/kg. Transport into low-Earth orbit (LEO) from the Earth presently adds more than $500/kg and thus confines goods produced in space to a tiny fraction of the potential terrestrial market (right of arrow 1 in fig. 1). Solar power stations are estimated to be economically feasible at $140/kg (refs. 3, 6). Supplying the bulk of the required construction material from the Moon at $20/kg (arrow 2) would clearly improve the economics and decrease the cost of the power supplied to Earth. If sources of industrial feedstock can be developed in deep space with costs of less than $0.5/kg (arrow 3) then many of the Earth-produced goods can be considered for potential space manufacture (ref. 1). It is conceivable that industrial material can be supplied at such low costs from the Moon or asteroids assuming normal industrial “learning curve” experience occurs.

Previous scientific exploration of the Moon and the vigorous ongoing program of lunar sample research and theoretical analyses allows us to study and plan in detail for obtaining lunar materials and chemically processing them. However, additional research is necessary and should be an ongoing component of the lunar base siting and operation. A general survey of the Moon is necessary – including the polar regions. There should be a close tie-in of the lunar sample and planetary sciences communities, with the engineering communities responsible for research and development of lunar bases and refining schemes. Above all, design of the lunar supply base should be approached so as to minimize total cost and maximize output to provide useful components of the lunar soil at points in deep space at the lowest possible cost per unit mass.

The following sections describe one approach toward a lunar base of minimal size which could be expanded in launch capacity from 30,000 tons/yr (bulk soil) to 600,000 tons/yr (beneficiated soil components) over a 5-year period making maximum use of lunar materials to minimize shipping from the Earth.

It is a pleasure to acknowledge the support supplied by the NASA-Ames Research Center in organizing the logistics and operation of this summer study. Particular appreciation is expressed to J. Billingham, W. P. Gilbreath, and B. Zeitman. Interactions with other participants, far too numerous to offer personal thanks by name, were intellectually stimulating, demanding, and rewarding. I wish to specifically thank J. McCoy (John- son Space Center), P. Vajk (Science Applications Inc.) and A. G. MacDiarmid (Univ. Penn.) for critical comments and suggestions concerning the text; deficiencies that may remain are of my own making. This work was conducted in part under NASA contract #NAS-09-051-001 to Universities Space Research Association which operates the Lunar and Planetary Institute (LPI). This is LPI Contribution No. 317.

LUNAR BASE TOUR

Conceptions of mankind’s first permanent installation on the Moon have tended to evoke paintings of either immense facilities containing hundreds of persons and

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**Figure 1.** Differential value of all goods produced in the U.S. (vertical axis) versus the intrinsic unit value ($/kg) of the goods (horizontal axis). Integral value in $B of goods with intrinsic values greater than 10, 20, 100, 250, and $1000/kg are shown at arrows.
enormous rocket traffic between the Earth and the Moon (ref. 7) or, on the other hand, simple and isolated extensions of the Apollo lunar module with little space, with limited capability and operated by only three or four persons. Concepts evolved during this study project a different style—one dominated for at least the first 5 years by the severe demands of utility and cost effectiveness. The principal function of the base is providing a supply of minimally-processed lunar materials to a collection point in deep space at the lowest possible initial cost, greatest reliability (attainable principally through simplicity of design) and with a straightforward plan for expansion of base output capacity by a factor of 20 over 5 years.

Figure 2 is a painting of the initial lunar supply base during the second lunar day of installation. All major features except three large adjustable mirrors to the east, west, and north of the solar array are depicted. Upon completion of the base, the three adjustable mirrors immediately to the east, west, and north, dominate the scene. Figure 3 is a scaled schematic of the base which will assist in locating the components described in the following tour. The solar array (item 6 in fig. 3) is about 180 m on a side (10 percent efficient cells) with a mass of 108 tons. Each of the three side mirrors (180 m wide, 260 m high) is individually adjustable to focus the maximum amount of sunlight onto the solar array and catch the last glimpses of the Sun after local sunset. Most importantly, it focuses the reflected sunlight from two to four solettas (large mirrors orbiting the Moon) which provide the equatorial base at night with one-ninth the full solar illumination adequate initially to maintain continuous operation of the mining, maintenance, and life systems, but not mass driver operation. Each surface mirror can be elevated from the horizontal to face the solar array at 45° past the local vertical. Although visually imposing because of their enormous width, 70-story height, and constant visible tracking motion night and day, they are very filmy and lightweight structures with a mass of 18 metric tons including hoists (estimated by E. Bock, study participant).

Figure 2.—Oblique view of the initial lunar base during the second lunar day of assembly as seen from several hundred meters above the landing pad.
Lunar base is on the Earth side of the Moon near a juncture region between Mare Tranquillitatis and the eastward highlands. At night, a pinpoint of light 8.7 km across is centered on the base and is visible from Earth as a variable star in the dark disk of the Moon. Four large, multifaceted mirrors, each 8.7 km in diameter and 240 metric tons in mass and in lunar orbits that are continuously sunlit, can illuminate the base with reflected sunlight. These orbiting mirrors are named solettas (refs. 8, 9). Continuous tracking of each mirror allows each to be sailed in its orbit about the Moon using the pressure of sunlight, so as to maintain the apolune of each soletta directly above the lunar base during the night. As seen from the lunar surface, the mini-suns sequentially rise in the west, cross the vertical meridian just higher than 30° above the horizon, and set in the east just after the following soletta rises in the west. Thus, there is a continuous input of solar energy for power, locally warming the extreme cold of lunar night and providing illumination for mining. The initial solettas were assembled in low Earth orbit from terrestrial materials, and then solar sailed to the Moon and into lunar orbit prior to the first landing of the lunar base components. The reflective area is increased thereafter using aluminum and fiberglass produced at the space manufacturing facility (SMF).

This soletta approach seems awkward on first consideration. However, the orbiting mirrors can be constructed in low Earth orbit and solar-sailed to lunar orbit without using propellant. They may also be capable of transferring significant cargo on a one-time basis. Such capability is not examined in this paper. Of immediate interest is the fact that use of solettas allows one to eliminate the need for about 400 tons of power storage equipment (example—flywheels) for nighttime operation of the base and also the 280 tons of propellant necessary to land the power storage units. Thus, the mass one transports to low lunar orbit could be decreased from 2600 tons (table 2 of Vajk et al., p. 65) to 1920 tons. It is conceivable that one can reduce the number of MDRE trips to deploy the base from LEO to LLO to two or even less by use of the solettas for illumination and possibly transport.

Restricting early mass driver operation to the lunar day, deploying a directable solar array and utilizing the solettas, enables continuous operations in construction and running of the base, minimizes the need for power storage and support machinery (the latter by a factor of 2) and greatly moderates the thermal day/night extremes at the lunar site.

Also visible from landing altitude is the 2-km-long, 5-m-wide mound of excavated lunar soil which covers the top of the tunnel containing the mass driver (item 1, fig. 3). A very slight dogleg is visible 200 m from the far end where the 3.8 kg slugs of packaged lunar soil are ejected from the deaccelerating buckets (item 1e, fig. 3). Three kilometers beyond is the first “Drift and Stabilization Section” (item 1f, fig. 3). At the end of the dogleg is a 100-m-diameter loop wherein the buckets are turned around and returned on a passive guideway toward the main tunnel and the loading facility. Almost all other features of the base, including the initial strip mine (item 5, fig. 3) are difficult to discern because of their small size, the blending covers of lunar soil, and the visual confusion of permanent disturbance patterns in the lunar soil resulting from the emplacement of the base and ongoing vehicular operations.

Technical details of the mass driver are given in a companion paper. Here the concentration is on layout related to installation, volume, and mass. The major mass driver acceleration sections are assembled from 23 connected subsections. The coasting sections can be
TABLE 2.—MASS-DRIVER SYSTEM

<table>
<thead>
<tr>
<th>Installation physically able to eject 600,000 tons/yr, powered for initial ejection rate of 30,000 tons/yr, extensively pretested on earth and/or LEO; unitized in 20-m sections for plug-together installation. Power (96 percent efficient in electrical to kinetic energy conversion; ejection of 30,000 tons/yr at 2.4 km/sec requires 6.4 MW average input power).</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. <strong>Accelerator Section</strong>: 300 m long, 1000 g, 3.8-kg payloads, 4-kg buckets (payload clamp and release mechanism), mass 100 tons, prefabricated as plug together 20-m units, housed in lightweight tunnel (5 m diameter) for thermal moderation and dust control, waste heat radiators, foundation points (empty cylinders with metal attachment points are buckets filled with lunar soil and binder (10%) at site, four foundation points per accelerator coil, cross-bracing above and beneath coils).</td>
</tr>
<tr>
<td>2. <strong>Drift and Stabilization Section</strong>: Passive guide rails, with slight lossiness to allow damping of transverse energy of the bucket, 2 km long, side and top covers to protect against dust and thermal changes, foundation every 20 m, 40 tons.</td>
</tr>
<tr>
<td>3. <strong>Payload Release and Bucket Sideways Deflection Section</strong>: Two bucket deceleration magnetic loops (Δν = 100 m/sec); ejection section; 1/2° deflection of bucket over 200 m (90 g side acceleration for 0.043 sec), four foundation points at each magnet section and every 2 m, 20 tons, &lt;10/cm/sec velocity errors at ejection in all axes.</td>
</tr>
<tr>
<td>4. <strong>Bucket Deceleration Section</strong>: 150 m long, 2000 g (8 kg overrun capacity), thermal and dust tunnel, four foundation points per deceleration section, waste heat radiators, cross-bracing, power accumulator and electrical refeed circuits, 50 tons.</td>
</tr>
<tr>
<td>5. <strong>Return Track</strong>: Passive guideway with thermal and dust tunnel; foundations every 20 m except on curves (eight foundations per 40 m), final deceleration section at entry to loading area and bucket checkout bay; 70 m/sec bucket velocity, 40 tons.</td>
</tr>
<tr>
<td>6. <strong>Initial Trim Station</strong>: Electrostatic focusing tube located 3 km downrange of release point, 3 m in diameter and 100 m long, trim velocity to 0.1 cm/sec, 30 tons, velocity sensors and control computer, 0.16 MW at full capacity (≈0.002 percent ejection energy) or 10 kW at 30,000 tons/yr, retraction hoists for focusing tube.</td>
</tr>
<tr>
<td>7. <strong>Final Trim Station</strong>: Electrostatic focusing tube located 150 km downrange of release point, trim velocities to 0.01 cm/sec, 30 tons, velocity sensors, 3 m by 100 m lightweight and segmented aluminum tube, 16 kW at 600,000 tons/yr, install to accept maximum capacity at once, retraction hoists for the focusing tube, solar array and power storage are located in a pit below ground level (ref. 11).</td>
</tr>
</tbody>
</table>

shipped in partially assembled condition to minimize shipping volume if necessary. All components of the mass driver system must be shielded from the extremely fine lunar dust. Thermal fluctuations must also be minimized to simplify design of the electronic and mechanical elements, maintain stable operating conditions, and prolong component lifetime. Radiation protection should also be provided for maintenance personnel. The MD system is laid out in a leveled trench 5 m wide, which is encased by heavy fiber reinforced Kevlar sheets laid directly on the lunar soil in the trench and supported on the side walls and ceiling by graphite Kevlar stays (20 m formed hoops of 1 cm^2 cross section) every meter down the tube. Small openings are provided for ejection of the slugs and escape of gas from space suit and repair operations. The stays and Kevlar mass is less than 20 metric tons. Lunar soil is heaped over the sides and top of the trench to a thickness of 4 m (300 g/cm^2 column density) thus providing an extremely stable thermal environment of ΔT -1 K (ref. 10) and complete radiation protection for repair and maintenance workers. Portable pressure chambers are provided which can be set up wherever in the tunnel detailed repair or maintenance is required. Accelerator sections can also be unplugged and rolled down the tunnel to the maintenance section.

Bags of lunar soil (≈3.8 kg) are ejected by the mass driver from the Moon. Downrange adjustment of the ejection velocity (i.e., velocity trimming) is accomplished by means of two trim stations. Each bag is electrostatically charged as it enters the trim station. In the station, electric fields parallel and perpendicular to the bag’s velocity vector adjust the bag’s trajectory and velocity to great precision. The two trim stations are located 3 and 150 km downrange. It is highly desirable to complete most final velocity trim (Δv) of the payloads close to the main base (ref. 11). This is because the trim energy is proportional to 1/2 mΔv^2 and will be of the order of 10 kW (m = 26.6 kg/sec, 80 percent duty cycle; v = 2.4 km/sec, Δv = 0.1 m/sec). This power is easy to obtain near the main solar array and no storage would be required. By trimming the dispersion velocity of the slugs to less than 0.1 cm/sec, the radius of the downrange guidance unit could be reduced and less energy storage and total station mass and complexity would be required at the downrange station than assumed by Vajk et al. (p. 61). Note that the solettas will not provide continuous sunlight at the downrange station.

Table 2 lists the systems features of the mass driver diagrammed in figure 3. Table 3 presents the estimated
### TABLE 3: LUNAR BASE COMPONENTS (30,000 TONS/YR INITIAL INSTALLATION)

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (tons)</th>
<th>Power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lunar surface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar array mirrors$a$</td>
<td>130</td>
<td>7.2</td>
</tr>
<tr>
<td>Mass Driver$b</td>
<td>250</td>
<td>6.4</td>
</tr>
<tr>
<td>Trim Stations</td>
<td>60</td>
<td>10.0</td>
</tr>
<tr>
<td>Loading facility (pressurizable)$b$</td>
<td>40$^c$</td>
<td>100.0</td>
</tr>
<tr>
<td>Stockpile bin</td>
<td>40</td>
<td>20.0</td>
</tr>
<tr>
<td>Packaging unit (pressurizable)$b$</td>
<td>70$^c$</td>
<td>120.0</td>
</tr>
<tr>
<td>Trucks (4 vehicles at 10 tons each)</td>
<td>40</td>
<td>250.0</td>
</tr>
<tr>
<td>Maintenance facility (pressurizable)</td>
<td>40</td>
<td>150.0</td>
</tr>
<tr>
<td>Habitat (pressurizable)</td>
<td>40</td>
<td>150.0</td>
</tr>
<tr>
<td>Binder for soils</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>800</strong></td>
<td><strong>8.7</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (tons)</th>
<th>Power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low lunar orbit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solettas — four orbiting mirrors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.7 km diameter, 600 tons each</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33.3° inclination, 3000 km apolune</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$a$ No significant power storage ($\approx$400 tons — Vajk et al., p. 61).

Initial solettas provide night time power.

$b$ Scale for 600,000 tons/yr - electrical components (230 MT), and 20 MT for tunnel stays and plastic coverings.

$^c$ Including 30 tons of packaging material for first year of operation.

$d$ Consumables and crew masses discussed in separate paper.

mass and power requirements of the major components. Construction of the mass driver was facilitated by the excavation of the trench by means of remotely-operated equipment deployed to the Moon following final site surveys and emplacement planning. The mass driver was fully tested in vacuum on Earth for 1 year prior to shipment. It was constructed in major 20-m sections specifically designed for "plug together" assembly with an absolute minimum of detailed work and extensively wired for remote (terrestrial or lunar base) monitoring of status, performance, and adjustments. Major components on each section (e.g., magnets, guide rails, radiators, monitors) were designed for quick plug-in and, where necessary, mechanical attachment without intricate assembly. Subassembly maintenance was designed to be done by removing accelerator units to the pressurized maintenance shop or utilizing portable pressure chambers. Foundation points for the mass driver are provided by mixing a binding agent 10 percent by volume (imported from Earth) with lunar soil and casting the foundation blocks in situ in lightweight plastic forms with the attachment points fitted in the mold.

LH₂ tanks of the space shuttles (8 m diameter, 24 m clear length) provide pressure vessels for the four major base units: (1) habitat; (2) loading facility; (3) packaging unit; and (4) maintenance shop. Units 2, 3, and 4 were designed as emergency habitats and to accommodate the extra workers during the initial emplacement period. All these units are connected by continuously pressurized tunnels with airlocks at each end. The loading facility and packaging units were sized initially for the full production capability of the base ($1.6 \times 10^6$ slugs/year at 3.8 kg/slug). In the automatic loading facility slugs are accepted from the stockpile bin, weighed, center of mass
...determined, the aluminum charging and tracking pattern sprayed on, correctly positioned, a last integrity check of the packaging performed and the slug placed in the bucket of the mass driver. The loading facility accepts buckets from the return tracks of the mass driver, off-loads the buckets, checks each bucket (containment and release mechanism, superconductor temperature and field, NDT structure check, scan of sleeve in container section, adjust sleeve for payloads of different density 2–6 g/cm³) and then transfers the bucket to the loading carousels. Subsequently, the bucket and payload are rechecked for total mass and center of mass and then transferred to the access section, equipped with a short section of superconducting guideway and accelerated into the main portion of the track at a very precise acceleration. Velocity is checked just prior to entry onto the main track and, if necessary, buckets not accelerated to the preducted velocity are shunted immediately to the return track. As needed, the passive cooling system of each bucket is refrigerated to insure the continued superconducting status of the bucket coils. Initially, the loading facility operates for 80 percent of the daytime duty cycle. It is expected that this will approach 90 percent of the full lunar month after 3 years of operation. The mass of the loading units is 40 tons and they consume 100 kW during initial daytime operations and 30 kW at standby.

Between the loading facility (item 2) and the packaging unit (item 4) is a stockpile (item 3) capable of holding a 10-day reserve of slugs (30,000 ton/yr launch rate). The bins are top-loaded and bottom-emptied by conveyor units that can sort slugs by length corresponding to different densities (2–6 g/cm³) of packaged material. All slugs are the same diameter. The bin is about 60 by 6 m and weighs 40 tons complete with conveyors. This unit is not pressurized, but is emplaced in a trench roofed with Kevlar over stays and covered by 3 m of lunar soil.

Packaging of each slug is accomplished by compressing 3.8 kg of material to 500 bars pressure (about twice the base-pressure in the slug at 10⁴ m/sec² acceleration) and then sealing in a 2-µm thick package of Kevlar which is then aluminized. Approximately 2 bars of bag tension is provided. Material compression requires 17 kW at the 30,000 tons/yr production rate. All grains packaged are less than 1 mm diameter. It is estimated the packaging unit may consume as much as 400 kW during full operation. Each slug is weighed and sized prior to delivery to the stockpile conveyor. In addition, the packaging units accept bulk soil from the two excavation trucks, screen the soil to remove nonfriable rocks larger than 1 mm, and dump the larger rocks by means of conveyors, in a small crater or returns them as fill to the soil pit.

The initial soil pit operation is very small by terrestrial standards. The solettas allow continuous operations and one small truck (10 tons inert mass, 30 ton payload) is able to satisfy the 30,000 ton/yr input requirement with 3 to 4 trips per terrestrial day, allowing only 80 percent availability. Considerable time is available for hauling. Three other vehicles are available and are generally involved in site preparation for expansion of the base, including leveling for future solar cell arrays and trenching for new facilities. Most of these highly repetitive operations are controlled from Earth. These trucks were used extensively in the emplacement operation and will receive far more use as the base expands. A conveyor system is to be introduced to accommodate the 600,000 tons/yr operation. Naturally, the remotely operating machine used for the preparatory excavations prior to manual landings has been dispatched on a route of unmanned scientific exploration. All the vehicles are powered by flywheels scaled to about 150 kW output. Repowering is provided from the main solar array (Vajk et al., p. 61).

Maintenance and repair for the trucks, major sections of the mass drivers, and other equipment, is done in a pressurizable and outfitted hydrogen/oxygen shuttle tank (item 7, fig. 3). It is equipped with a large air lock which can accept 3-m-diameter objects and has a clearable depth of 22 m. The back bulkhead contains an air lock and covers a bunk area and control system for depressurization operations and equipment which should not be subjected to vacuum. A 100-m-long approach ramp allows truck access to the main air lock and is stabilized with a binder to minimize dust entry to the maintenance facility. Mass of the facility is about 40 tons and it draws an average 150 kW.

Cryogenics storage (item 9, fig. 3) is provided in the permanently shadowed area under the eastward-facing mirror attached to the main solar array. Chemical rockets touchdown on a 100 m diameter landing pad (item 10) of stabilized lunar soil located 5 km to the south. Stabilization is required to prevent dust disturbance which obscures the landing and might coat the solar array and heat radiators at the lunar base. There are stabilized haul roads between the landing pad, maintenance and loading facilities, packaging unit and the pit (item 11).

The Habitat (item 8) is the residence and communications and control center of the base. It houses the 10 personnel who stay on station for 6 months, but 50 percent of whom are rotated every 3 months, either
to Earth or to the space manufacturing facility (SMF). In effect, the lunar crew is an extension of a terrestrial control center which operates and monitors equipment round-the-clock for both site preparation operations by the remotely-controlled excavators and mass-driver operations. No estimate is provided here of the necessary terrestrial manning level. It is noted that studies of the degree of possible automation and man-hours/operating hours of the major lunar units are required and afford a very real opportunity for spinoff to many economically significant tasks on the Earth. Possible examples of terrestrial application include development of remote operation of Earth moving equipment for excavation and leveling, systems monitoring and control of undersea oil production or glass production, quality inspection of agglomerated materials (encased) by thin films. Joint NASA/industry workshops on specific topics would clearly be appropriate. There is high bandwidth continuous communications between the terrestrial center and the lunar crew complete with a full-color, wall-sized television system for weekly staff meetings between the entire lunar crew and the terrestrial staff and, as necessary, the staff at the SMF. Basic functional volumes in the habitat are: (1) communications and control center; (2) main (TV screen) and adjacent recreational rooms; (3) galley and dining area; (4) 12 private rooms; (5) storage locker; and (6) the life-support room. The habitat is similar in design to those employed in low Earth orbit and at the SMF with modifications necessary for horizontal emplacement beneath the lunar surface.

Two unmanned trim stations (items 1f and 1g, fig. 3) are located 3 km and 150 km downrange from the mass driver. Only the long, but lightweight correction tube is present above the surface at each station. Some consideration was given to placing the trim stations behind revetments. However, occasional misses by 3.8 kg slugs moving 2.4 km/sec generate large craters and would require major revetment repairs. Instead, the supporting mechanisms for the initial correction tubes were designed to pull the correction tubes into a trench and beneath the surface in 1/20 sec if a bag is observed either to rupture or to be badly off course on leaving the mass driver. Small blast deflectors are designed into the front of each of the trenches to insure that all the debris will pass over the recessed correction tube.

The lunar supply base would offer a viewer a slowly changing scene of mirrors following the Sun during the day and the solettas at night. The steady expansion of scratch marks on the lunar surface by the mining operation contrast to the occasional quick hops downward by the 100-m-long, but lightweight, correction tubes to avoid certain destruction by a direct hit by one or more misedected bags of lunar soil. The fast action, the packaged slugs of soil leaving the Moon at 2.4 km/sec, would not be visible until the launch rate exceeded 4 or 5 per second. At that time one could stand underneath the entry tube to the first trim station and see a sparkling line of light, something like a stream of water, wobble its way into the mouth of the correction tube. On exiting, the stream would be rock steady and point arrowlike to the eastern horizon and the location of the final trim station. Persistence of vision would tie the thousands of separate slugs into a faint pipeline of light leaving the Moon. A strobe light shining across the exit mouth of the initial trim station could be flashed in synchrony with the exiting packages of soil to produce the visual illusion at night of a single, slightly blurry bag of soil suspended above the ground. Of course, over the interval of 1.25 min the illusion would be composed of the reflections from about 1000 soil packets at an ejection rate of 600,000 metric tons each year.

**Implacement Strategies**

Five general considerations influence the design and operation of the initial base suggested in this study: (1) need for continuous operation in order to minimize the size of the initial and final base; (2) maximum use of remote control and assistance from a terrestrial control center of as much of the process monitoring, equipment status, vehicle guidance (e.g., mining), administrative assistance, and problem analysis as is possible; (3) all initial units should be constructed as separate plug-together units which are as large as possible and still convenient to land, manipulate, and place and plug together in the quickest possible time by a minimum crew; (4) the mass driver, sieving/packaging units should be scaled to handle 600,000 tons/yr; and (5) the basic operating crew should have as their main functions maintenance and site preparation for future expansions. All aspects of the design, emplacement, and operation of the base are greatly facilitated if continuous sunlight is available at the base. Thus, four 8.7-km-diameter mirrors in continuously illuminated orbits about the Moon are assumed to be operational before emplacement of the first major units of the base. These mirrors are discussed in the “Soletta” section.

Expansion of throughput by a factor of 20 (from 30,000 to 600,000 tons/yr) can be accomplished through three steps: (1) steady additions of nine more 7.2 MW solar arrays (each supplemented by three surface
mirrors); (2) addition of a mineral separation facility, haul trucks and a fiberglass/aluminum facility for the production of bags for packaging the soil slugs; and (3) enlargement of the orbiting mirror arrays to provide constant solar illumination during the lunar night. Total mass of the mature lunar operation should be less than 3000 tons on the lunar surface and 8640 tons of solar reflectors in lunar orbit. Total base personnel should increase to about 50 at the end of the 5-year growth phase, requiring additional habitats.

The following scenario for deployment of the initial base following site selection is predicated on the extensive development and checkout on Earth and possibly in Earth orbit, of the unitized (plug-together) base which is shipped as two major freight subsystems from low Earth orbit (LEO) to low lunar orbit (LLO) by the first mass-driver tug. The mass-driver tugs have payloads of approximately 1300 tons from LEO to LLO. Similar problems were faced in development of the petroleum fields on the North Slope of Alaska. Habitats weighing up to 800 tons were preassembled in Seattle, Washington and shipped to the North Slope and installed in 4 months on prereadied sites (ref. 12).

Each freight unit is soft-landed (300 to 600 tons) as a single unit following LLO insertions (ref. 13). Freight unit no. 1 contains two automated (Earth-controlled) excavation units. On landing, these units unload themselves, assist in unfurling from the landing vehicle two 150 kW solar arrays, which operate electrolysis units for regeneration of fuel cell hydrogen and oxygen (or recharging flywheel power units), and then proceed for the next 7 months under terrestrial control to make the major leveling excavations for the mass driver, processing units, large solar array, and habitats. These excavation units will be operated exclusively for site preparation for the 5-year period of base development. The mass driver immediately returns to Earth after deploying the first freight unit. Freight unit no. 2 and the construction force of 25 persons (personnel transported by chemical rocket from LEO) arrive 7 months later and begin emplacing the various units over a 4-month period. The orbital mass-driver tug immediately returns to Earth after deploying two catcher/freight units at L2.

Base construction would consist of the following deployment sequence: (1) on lunar day 1 — habitat and maintenance emplacement and coverage, start of solar array emplacement, layout of the 23 major accelerator units and 200 coast sections of the mass driver along the excavation for the track; (2) on lunar day 2 — emplacement of the solar array completed, mass-driver layout completed, assembly of the thermal and dust tunnel progresses with mass-driver assembly, assembly of the initial trim-facility completed, and emplacement of the screening/packaging facility completed; (3) on lunar day 3 — crew of 6 translates to the site of the final trim facility to prepare the site and emplace the unit (2 lunar days for job), assembly of mass driver is complete and alignment and test shots are made following completion of work at the remote site and deployment of surface mirrors is started; and (4) on lunar day 4 — emplacement of surface mirrors and the final trim station is completed and full operational tests are conducted. At the end of lunar day 4, the remote crew returns to the lunar base and the 15 construction workers then return to Earth. At the start of lunar day 5, 1 year after touchdown of freight unit no. 1, the lunar base is ejecting during the day bulk lunar soil to the two catcher/transporters which can transfer 2300 tons/lunar month of bulk lunar soil to the SMF by 1 year after the start of lunar base construction. This soil will be useful for reaction mass, shielding, checkout of the mineral dressing and chemical processing equipment, oxygen generation, and fiberglass production.

**INCREASING CAPACITY AND DECREASING UNIT COSTS**

Increasing the capacity of useful material ejected to deep space requires: (1) the addition of nine more solar arrays, (2) introduction of soil separation and beneficiation equipment, (3) an increase in the hauling capacity from the mining areas to the soil processing unit by a factor of 40 to 60, (4) the emplacement of a waste material dump system (very likely a fixed conveyor dumping into a small crater), and (5) enlarging the orbiting mirrors by a factor of 9 in area. It is possible that the availability of Lunar samples will permit the design, construction and deployment of electrostatic separators as part of the initial soil sieving and packaging unit. If not, the separation units can be added. Installation of the separation unit will allow one to send only the most useful component (83 percent anorthite, 19 percent ilmenite) of the lunar soil to space, and thus maximize raw material input to the SMF for manufacturing Al, Si, O, Ti, and Fe. This will be equivalent to a factor of 3 to 4 increase in the delivery rate of economically useful materials. Trucks and/or conveyor systems necessary for increasing the haulage capacity, can be delivered yearly from Earth. Trucks and conveyors adequate for the task will have a mass less than 60 tons (Williams et al., p. 275).
It is assumed that most of the solar cells and reflectors (surface and orbital) for the additional power units will be produced at the SMF from processed lunar materials and delivered to the Moon for installation. Pre-assembly and checkout at the SMF of these units is assumed so that only site preparation and deployment will be required of the lunar crews. The costs of all of the additional arrays (factor of 20 increase in power) should be less than the cost of the original 7.2 MW unit. It is possible that the additional solar arrays will be center-mounted on tall support columns and actively directed toward the Sun. This involves much stronger support columns than the mirrors, but almost eliminates site preparation, makes tracking of the sollettas more precise, and maintains a lower temperature for the array.

Cost per unit ($/kg) of the delivered materials can be progressively reduced by: (1) installation of a plant for the production of a bagging material made of fiberglass/aluminum composite; (2) use of liquid oxygen produced in space from lunar materials and stored in low lunar orbit for the lunar landing rocket; (3) recovery at the lunar surface of hydrogen and oxygen from lunar fines (see Williams et al., p. 275); (4) facility for the fabrication of pressure vessels, structural materials and other redundant items from the fiberglass/aluminum composite and locally produced ceramics and glasses (especially foundations and stabilized soils); and (5) increasing the "closure" ratio of the life-support systems. By the end of year 5 of base operations, the operating costs should be dominated by crew rotation costs, salaries and maintenance expenses (excluding capital investment of further expansion operations).

Approximately 1 ton of liquid oxygen is required to land 1.2 tons of payloads on the lunar surface from low lunar orbit and return a lunar shuttle to low lunar orbit (Vajk et al., p. 61). It is not clear at this time whether the oxygen production can best take place at the SMF, the lunar base, or both, but any of these options in effect increases the useful payload fraction of mass driver freighter to the Moon by a factor of 2. Thus, very large cost savings are possible by quickly initiating production of liquid oxygen from lunar materials for use in operations between the lunar surface and low-lunar orbit.

PACKAGING OF THE LUNAR MATERIALS

Each unit of lunar soil ejected from the Moon must be contained in a thin, aluminized packet. This packet must contain the powdery material for mechanical handling, prevent breakup of the slug and dust generation during ejection by the mass driver, and accept uniform electrical charging for electrostatic velocity trims and high radar and optical reflectivity. In addition, there must be uniformity of packaging from one slug to the next with respect to trajectory perturbations by light pressure, the solar wind, and magnetic and gravity gradients. The packages must break apart uniformly for removal of the encapsulated material, and the packet material should be useful for either recycling to the Moon or in some other derivative application. Packaging must be done in a vacuum so that no outgassing will occur during the coasting phase which would perturb the trajectory of the slug of lunar material. The total mass of bagging material used each year ($\dot{M}_b$) is related to the total mass of lunar material to be ejected each year ($\dot{M}$) by

$$\dot{M}_b = 2\dot{M}(\rho'/\rho) \cdot (\Delta P/Y) [(4 + L/R)/(L/R - 2/3)]$$

for cylindrical slugs (ignoring slight taper of the cylinder of soil) with hemispherical end caps where $R$ is radius of the cylinder, $L$ is the length of the cylinder, $\Delta P$ is the pressure the bag applies to hold the slug of soil together, $Y$ is the yield stress of the bag material, $\rho'$ is the density of the bagging material, and $\rho$ is the density of the compressed lunar soil. Thus, to first order the required mass of bagging material is independent of the size of the slugs ($m$) made of the ejected lunar material. The mass of one bag ($m_b$) is simply

$$m_b = \dot{M}_b / \dot{N} = \dot{M}_b (M_g/\dot{M})$$

where $N$ is the number of slugs produced each year.

Bag pressure will be adjusted to about 2 bars (a factor of 10 in bag yield strength is included for safety), the bulk lunar soil compressed to a density of about 2.2 g/cm$^3$, and $L/R \approx 12.66$ for the present lunar mass driver. The compression requires a pressure of about 500 bars and is twice the pressure the lunar material will experience at the base of the slug during the $10^4$ m/sec$^2$ acceleration from the Moon. There should be negligible rebound of the material following acceleration termination or ejection from the bucket. Grinding between soil grains in the bag should provide a sink for vibratory and compressive disturbances during launch and release. A continuous power supply of about 17 kW is needed for the compression of 30,000 tons/year of slugs. Clearly, the bagging material cannot sustain the full stresses of the 1000 g (±60 g’s transverse) launch environment. It is assumed that the bucket will be designed to securely contain the bag of soil against these accelerations without tearing the bag, permitting a smooth axial release of
the bag at the launch (ejection point) and a means of containing bags which do not eject.

In order to keep the base design and functions simple at first, it is appropriate and economically reasonable to import the packaging material from Earth. A high strength synthetic such as Kevlar \( Y \approx 34,000 \text{ bar and } \rho' \approx 1.5 \text{ g/cm}^3 \) seems completely adequate. The total mass of bagging for 30,000 tons of ejected mass would be about 33 tons. This is an acceptable penalty for initial operations. However, as the operations increase in scale, it becomes desirable to install a plant on the Moon to produce an aluminum/fiberglass composite sheet. It is assumed that the fiberglass will be produced on the Moon and the aluminum returned from the SMF by the start of the second year of operation of the lunar base. Assuming the composite has a yield stress of about 10,000 bar (ref. 14), then one must manufacture 2.2 kg of packaging material on the Moon for every ton of ejected material or 1320 tons/yr for 600,000 tons/yr of ejected material.

Details of lunar fiberglass production from lunar materials are discussed in a companion paper (Ho and Sobon). A 10–20 percent increase in the capacity of this production facility and the addition of fabrication shops would permit the construction of a large number of items for subsequent expansion of the lunar base such as large pressure vessels, structural fiberglass composites, electrical cable, glass and ceramic structural elements, pipes, acoustic panels, and so on. A fiberglass production facility adequate to produce 3000 tons/yr of finished fiber should have a mass of less than 100 tons. Lay-up and fabrication facilities should have a mass of about 70–100 tons. Refer to Criswell (ref. 15) for a general outline of material flow for production of bags on the lunar surface.

**LUNAR BASE POWER REQUIREMENTS**

Ideally, all operations concerned with the lunar mining and mass ejection should be conducted continuously with only scheduled maintenance shutdowns. In this manner the base could be about one-half the size required for an operation conducted only during the lunar day. Continuous operation is only possible if a source of continuous power is available. Continuous power could be obtained by increasing the size of the solar array and storing power for nighttime operations in fuel cells, flywheels, or batteries. Flywheels appear to provide the highest energy density and infinite recycling but impose a weight penalty slightly less than 1.2 to 1.3 kg/kW-hr including transport fuel for delivery to the Moon (P. Vajk, p. 61). Other schemes, such as a nuclear power plant (legal problems) or a space power platform beaming microwaves to the Moon (depend on start of SPS production) appear less than optimal initially. It is suggested here that mirrors orbiting the Moon and reflecting sunlight to the base during lunar night may be a reasonable solution. First, an overview of the power consumption is presented.

The major blocks of power which must be provided for operation of the minimum base are, first, for the ejection of 30,000 tons/yr (0.967 kg/sec continuously) of material during the lunar day (0.5 duty cycle of the lunar day) and, secondly, for the mining and packaging operations which are best conducted continuously (Williams et al., p. 275). Notice that 2.9X10^6 J/kg are required to accelerate material to the 2.4 km/sec ejection velocity. Assuming the mass driver is 96 percent efficient in converting electrical energy into ejection energy and 10 percent of the daytime ejection period (0.9 operating fraction per terrestrial day) is lost due to maintenance downtime the average input power \( P(MD) \) is:

\[
P(MD) = \frac{(0.967 \text{ kg/sec})(2.88 \cdot 10^6 \text{ J/sec})}{(0.5)(0.9)(0.96)} = 6.4 \text{ MW}
\]

Approximately 2.2X10^9 W-hr are required during each lunar day for mass driver operation. It is clear that the mass driver control system must be designed to accept a continuously changing launch rate of payloads in order to avoid the penalty of very large power smoothing units. Base operations are anticipated to require the following units of power: Habitat ~ (16 kW/person, 10 persons) ~ 160 kW; trucks ~ 250 kW; sieving, packaging, and maintenance facility and miscellaneous power requirement ~ 400 kW for a total continuous input of \( P(B) = 800 \text{ kW} \). About 5.4X10^8 W-hr of electrical energy are required for operation of the base, exclusive of the mass driver, each lunar month. This corresponds to 20 percent of the total monthly power input of the solar array. Thus, the average daytime power requirement is \( P_0 = 7.2 \text{ MW} \), whereas the nighttime requirement is about an order of magnitude less at \( P(N) = 0.8 \text{ MW} \).

It is assumed that the power will be provided by a solar cell array \( F = 0.1 \) efficient in solar to electrical energy conversion efficiency including power conditioning; 15 tons/MW area power density). Two innovations are suggested to minimize the size of the solar array and the capacity of power storage devices (e.g., fuel cells, flywheels). First, the solar array will be surrounded on
three sides by three lightweight mirrors which are independently adjustable from the horizontal to 45° local vertical. These mirrors are of width equal to that of the side length \( L_S \) of the square array and a length of \( h = 1.414 L_S \). Second, two to three orbiting mirrors will provide reflected sunlight during the lunar night adequate to operate the base (0.8 MW), but not the mass driver. By the third year of base operations, these orbiting mirrors (solettas) can be increased in size by a factor of 9 using fiberglass and aluminum from the SMF; this will permit operation of the mass driver during the lunar night and thus increase the mass ejection capacity of the base by a factor of 2 with little or no additional ground installations.

Figure 4 depicts the power profile for the solar array/mirror system augmented by soletta illumination at night. Region 1 corresponds to a sine dependence of the power output of the flat solar array, between sunrise and sunset. The total watt-hours (WH) output in region 1 is \( (2/\pi)P_O L_d \) (length of lunar day) where \( P_O = 7.2 \) MW. Actually, the sine distribution of output power would not be realized due to increasing external reflection and scattering of the incident sunlight back to space as the illumination angle of the solar cells approached the horizontal (0°). However, use of the mirrors greatly improves the power input because the sunlight is then never incident on the solar cells at less than 45°. Continuous adjustment of the elevation angles of the mirrors on the western and eastern edges of the solar array allows the reflection of sunlight onto the array to produce additional power in region 2. Lunar reflectors are effective whereas times-2 solar concentrators are not competitive with solar cells alone for space power stations since they can be continuously directed toward the Sun (ref. 16). The Lunar case is different in that the “times-2” concentration need only occur (optional) about lunar noon. Otherwise, the concentrators suggested here simply maintain the solar radiation to the solar array at a high value (>1 solar constant) throughout the lunar day. Let \( E = 0.1 \) be the conversion efficiency of solar energy into electrical output of the array and allow for 10 percent average reflection losses \( (c) \) at the mirrors and the surface of the solar array, then we can estimate the area \( (A_3) \) of the solar array (where \( P_S = 1.4 \times 10^3 \) MW/km is the solar constant) to be:

\[
A_3 = \frac{(P_O/P_S)}{[1 + (1 - c)(2/\pi)]E}
\]

For the stated values of the quantities in the equation we have

\[
A_3 \sim 0.0327 \text{ km}^2, \quad L_S = 181 \text{ m}
\]

The mass of the solar array would be 108 tons. The mass of the three adjustable mirrors, support beams and hoisting mechanisms would be about 18 tons (E. Bock, Convair, San Diego) using two compression beams and side beams for each mirror and cable hoists. Reflectors are useful for power conditioning on the lunar surface, in spite of the large area of the reflectors, due to low gravity and lack of weather and weathering effects. This approach would be impractical terrestrially. Major future considerations in evaluation of this approach are (1) effects of running the solar cell array at two solar concentrations for about 1/4 of the lunar day and (2) conditioning of the front surface of the solar arrays to minimize reflection of sunlight at small angles of incidence. Alternatively, it may be advantageous to center-mount the array (or a segmented array) on a tower of height one-half the length of the array and point the array continuously toward the Sun or the particular soletta providing nighttime illumination. Use of a tower would allow the solar cells to operate at lower temperatures during the lunar day.

Region 3 (sunrise and sunset) corresponds to either the east or west mirror viewing the Sun while the general terrain is dark. Some power can be received during this time due to the slow rotation of the Moon and the large height of the mirrors \( (L_h \approx 260 \) m). The time interval \( (t_d) \) between sunset at the base and the top of the mirror at the equator for a spherical moon is given by

![Figure 4. Power profile of the lunar base during a complete lunar month (power consumption in megawatts, vertical axis; time past sunrise, horizontal axis).](image-url)
where $\dot{\Omega} \approx 0.53^\circ$/hr is the rotation rate of the Moon, $R = 1738$ km (radius of the Moon), $L_h$ is the vertical dimension of the array, and $\phi$ the angle of the mirror with respect to the direction to the local sunset direction ($=45^\circ$). Thus, for $L_h = 260$ m we have $t_i = 1.57$ hr. The pre-sunrise and post-sunset operations can add as much as

$$2\times(1/2) \times (7.2 \text{ MW}) \times (1.57 \text{ hr}) \approx 0.11 \times 10^8 \text{ W-hr}$$

Large elevation difference are available in the lunar highlands. It is not unreasonable to expect that one could locate mountain peaks within 30 km of the base site which might be 2 km higher than the base. The peaks would be exposed to the Sun at least $5.2$ hr longer than the base and possibly much longer if the local eastern and western horizons are significantly depressed below the horizon of the spherical Moon. Reflectors on the scale of 600 m (length) by 300 m (height) adjustable over $95^\circ$ azimuth could contribute at least $0.74 \times 10^8$ W-hr to the nighttime power budget or increase the operating time of the mass driver by $3$ percent or more. Such surface mirrors could contribute $2$ percent to $14$ percent to the estimated nighttime energy budget of $2.7 \times 10^8$ kW-hr indicated as region 4 in figure 4, depending on local geometry.

An interesting option to conventional solar cells may be available for use on the Moon by using photoemission and/or thermionic emission. The basic power unit would consist of three aluminum strips which could be vapor deposited on the bottom and sides of a rectangular trench (possibly 3 or 4 cm wide and deep, and about 1 m long). The trench, one of tens of thousands of identical closely spaced trenches, would be oriented with its long axis in the east-west direction. The bottom of the trench would next be evaporatively coated with a photoemissive/thermionic material. Sunlight would produce a flow of electrons from the trench bottom to the sides evoking a small potential difference which can be regulated to control the current flow and thus maximize the power output. The mass of the aluminum and electron emissive materials required would be trivial compared to the equivalent areal mass of solar cells, whereas the mass of ancillary parallel and series hook-up wires and power conditioning equipment should be similar to that needed for solar cells. Conversion efficiencies of about $5$ percent are thought to be possible (ref. 17). This photo-similar effect is likely to operate naturally on the Moon in the levitation of lunar dust (refs. 18, 19).

Further experimental and theoretical research is needed and should be given high priority for application not only to lunar surface operations, but also for possible space power systems which could be constructed largely of lunar materials.

As noted earlier, about 400 tons of power storage units ($1.2$–$1.5$ kW-hr/kg) would be required to power the station over one lunar night. In addition, about 300 tons of propellant would be required to soft-land the extra mass. Finally, as base activities increased, the storage capacity would increase linearly with the scale of nighttime operations. Total mass of power storage units could approach 6000 tons on the lunar surface and 4000 tons of propellant in LLO for delivery. For these reasons, the alternative approach of deploying large mirrors in lunar orbit which could power, illuminate, and warm the base at night and permit 24 hr a day operation even during the lunar night, is suggested.

**SOLETTAS**

Billman et al. (ref. 9) and Ehrcke (ref. 8) both proposed that large mirrors be orbited about the Earth to illuminate cities, agricultural regions, ice fields blocking navigation, and solar power installations. Orbiting mirrors are far better suited for lunar than terrestrial use due to the absence of a lunar atmosphere, availability of continuously illuminated lunar orbits, the long period of such lunar orbits, relatively small change in slant range during the illuminating period, and the option of precessing the apolune of each mirror over the cycle of the lunar month in order to keep the apolune over the longitude of the lunar base (David Ross, Stanford Univ., Aeronautics and Astronautics Dept., personal communication). The amount of reflective area required in space is independent (to first order) of the altitude of the solettas for continuous coverage. The fundamental design constraint is that the minimum size of spot ($D_3$) on the ground is determined by the angular size of the Sun ($\alpha \approx 9.3 \times 10^{-3}$ rad) and the slant range ($h$) between the orbiting mirror and the ground spot where $D_3 = h \alpha$.

The mirrors must be constructed of individual flat segments or submirrors which must be individually directed toward the desired ground spot. Submirror size is limited by the required flatness of the mirror surface. The segments can be directed toward a reference laser beam at the receiving site. For one solar constant of illumination the mirror must be the size of the ground
spot; therefore, the diameter of the mirror \((D_M)\) will also be \(D_M = ha\). In the lunar case the use of the three movable mirrors on the ground (or a tilting solar array) which surround each solar array will permit considerable smoothing and effective concentration of the solar power to the array in response to non-normal incidence of the sunlight reflected to the site by the orbiting mirrors. The three ground mirrors become more effective as the maximum viewing angle of the orbiting mirrors above the local horizon increases. Use of ground mirrors or tilting arrays avoids increasing the size of the orbiting mirror above \(D_M = ha\). However, attention must be given to array spacing on the lunar surface as the ground installation grows in order to insure that there is no significant shadowing of portions of the array by foreground units.

The suggested lunar system consists of four solettas trailing each other along a high inclination, low altitude orbit. It is assumed the initial solettas are sized to provide one-ninth solar illumination (average) to the arrays to power the lunar base through the night. These one-ninth solettas would be constructed in low-Earth orbit from components supplied from Earth. Figure 5 depicts the low altitude, high inclination orbit. In this example, the average slant range is 2800 km and \(D_S = D_M = 26\, \text{km}\). For the initial one-ninth solar illumination at the base \(D_S = 8.7\, \text{km}\). A slight increase of the eccentricity of this orbit would permit overlap of the viewing periods (57.2 min; 24.4 percent of the orbit). Decreasing the inclination of the orbit increases viewing time but also the slant range to the base and therefore requires an increased mirror size.

Four mirrors, each about 40 km\(^2\) area (240 tons per mirror at 6 g/m\(^2\)), could meet the overnight power needs of the base and prevent the extremely prolonged cold soak of lunar night by providing one-ninth the full solar constant. For an orbit with a perilune of 500 km, apolune of 1610 km, and inclination of 33.3\(^\circ\), each mirror would rise in the southwest (or northwest), attain a maximum elevation of 20\(^\circ\) in the south (or north), set in the southeast, and be visible above the horizon for 57.2 min per orbit (24 percent of the 3.9-hr orbit). The projected spot from such a satellite would be extremely elongated due to the low sighting angles. However, the three ground mirrors could be continually reconfigured to reflect soletta light into the collecting array thus obviating the low illumination angle. Assuming the launch costs ($650/kg) to an Earth orbit of altitude greater than 1000 km dominate the production and assembly costs of the mirrors, an investment of

Figure 5. Three views of a low altitude soletta orbit about the moon. Four 8.7-km diameter solettas would be required to provide overlapping illumination of the base with one-ninth solar constant input to the solar array.
$624 million would be required for the initial orbiting network. This cost could be reduced sharply by utilizing the aluminum in shuttle tanks in the mirror structure. Savings in base construction time, continuous equipment usage, and minimization of power conditioning and storage should justify the expense. The mirrors would transport themselves by solar sailing from Earth orbit to low lunar orbit and might be used to transfer significant payloads as well to lunar orbit depending on the time constraints. It will be necessary to continually track and solar-sail the solettas. There must be a continual reconfiguring of the individual submirrors during the lunar daytime portion of the orbit and when the base is on the day side in order to utilize solar pressure to maintain the proper orbital elements. Presumably this can be a highly automated process.

NASA programs for solar-sail development have established the characteristics of a large space mirror constructed out of aluminum and plastics which could be deployed in the mid-1980's. Areal densities as low as 6 g/m² can be expected (refs. 20–22). Thus, one low altitude soletta providing full solar illumination at the lunar surface would have a mass \( M_s = (6 \text{ tons/km}^2)(\pi/4)(26 \text{ km})^2 = 3185 \text{ tons}. \) Extensive use could be made of fiberglass and aluminum from the initial production runs at the SMF to produce the full size solettas for final production expansion of the lunar supply base. If a technique can be developed to produce thin-film aluminum without a substrate, then very little material would have to be brought from the Earth. The solettas could be sailed directly from the SMF to lunar orbit without the expenditure of reaction mass or energy.

The relative efficiency of the solettas in providing energy increases as the size of the lunar base increases to fill the 26-km diameter of the minimum illuminated spot. The initial installation on the lunar surface utilizes only \( 9 \times 10^{-5} \) of the incident sunlight and the 600,000 tons/yr installation \( 2 \times 10^{-3} \) of the incident sunlight. Thus, a soletta system could support the ejection of up to \( 3.4 \times 10^8 \) tons/yr of lunar material with a base installation of 45 to 50 percent less total mass than without the orbital reflector system.

CONCLUSION

Construction of a lunar supply base in support of suggested scenarios for space manufacturing (refs. 23–24) does not appear to present insurmountable problems. The main challenge is in reducing the overall costs, development and deployment times and designing highly automated systems capable of maintaining continuous high throughput of soil into space. The main research items are in the direction of enhancing rather than enabling base deployment and operation. Specific research and development objectives include the following:

1. Preparation of the site of the base by remotely controlled excavation equipment.
2. Determination of reasonable designs for maximum unitization and pretesting of base units for minimum time of implantation.
3. Determination of schemes for remote monitoring and control base operations to minimize base personnel and to maintain highly reliable performance.
4. Development of one-ninth solar illumination solettas for continuous operation of the base and full-scale solettas which would utilize lunar materials for the bulk of the mirror structure and reflective surface.
5. Production of oxygen on the lunar surface and in space for propulsion and secondary life support.
7. Production of nonorganic binders on the Moon for producing foundations, haul roads and other stabilized surfaces, and for binding fiberglass should be researched and developed.
8. Investigation (theoretically and experimentally) of the feasibility of solar power conversion by photovoltaic and thermionic devices which could be emplaced on the Moon using 10 to 100 times less materials imported from Earth than would be necessary for conventional solar cells.
9. Exploration of the Moon for concentrations of trace materials – especially volatiles such as water, carbon, nitrogen, sulfur, chlorine and copper, zinc, lead, and hydrogen.
10. General exploration of the options for materials substitutions with respect to expected major products in space and optional processing schemes.
11. Exploration of alternative uses of lunar materials and a lunar base at an earlier stage to extend the capabilities of the present space transportation system and to extend space exploration and exploitation.

It cannot be overemphasized that additional options not mentioned in this study should be explored. Conceptual advances can be expected which would lead to overall space systems that could be less expensive, deployed faster, provide bulk lunar soil at lower costs and over a greater range of space between the Earth and
the Moon, and possibly sharply reduce the cost of Earth-to-orbit transportation compared to this scenario. As the cost of unprocessed lunar materials and chemical feedstock obtained from lunar materials decreases, the magnitude of space operations will expand rapidly with only moderate increases in the minimum necessary funding.

REFERENCES


