

LUNAR RESOURCES AND THEIR UTILIZATION

William C. Phinney, Chief, Geology Branch, Lunar and Planetary Sciences Division
NASA Johnson Space Center, Houston, Texas

David Criswell, Staff Scientist
Lunar Science Institute, Houston, Texas

Eric Drexler, Student
Massachusetts Institute of Technology, Cambridge, Massachusetts

James Garmirian, Student
Hope College, Holland, Michigan

Abstract

Lunar surface materials offer a source of raw materials for space processing to produce structural metals, oxygen, silicon, glass, and ceramic products. Significant differences exist, however, between lunar surface materials in the highlands and those in the maria. In the highlands the soil depth is at least an order of magnitude greater, Al:Fe is ten times greater, the content of plagioclase ($\text{CaAl}_2\text{Si}_2\text{O}_8$) as a source of clear glass is three times as great, and the content of Ti is at least an order of magnitude lower. Bulk lunar soil can be utilized for fiberglass and ceramic products. Evaluation of the extractive metallurgy and chemical operations associated with carbothermic and silico-thermic refinement of lunar regolith suggests that Fe, Al, Si, Mg and probably Ti, Cr and Mn can be recovered, while oxygen is produced as a by-product. The existence of multiple paths and of analogies to past industrial practice give high confidence of feasibility. A conservative plant design yields its own weight in oxygen, silicon, and structural metals in less than six days. Power requirements for a throughput of 300,000 tons per year is less than 500 megawatts. The processing is done more economically in space than on the lunar surface.

Introduction

Lunar surface materials have been proposed in many future planning programs as a source of raw materials for fabrication of a variety of structures in space.^{1,2} Most studies of this type have pointed out the general composition of lunar soil and suggested, in fairly general ways, the potential separation processes to obtain metal or other products.³ Some studies have detailed the processing of lunar soils to produce specific products such as oxygen, water, or individual metals.^{4,5,6} This paper presents, first, a review of the physical and chemical nature of lunar surface materials, second, a relatively comprehensive preliminary design of a moderately large-scale processing system to produce structural metals, oxygen, silicon, glass, and ceramic materials all of which are suitable for fabrication of large structures in space, third, an evaluation of the location of the processing plant, and fourth, estimates of the energies, masses, and volumes required for the processing equipment.

Characterization of Lunar Surface Materials

The lunar regolith consists of comminuted material resulting from meteoritic impacts on the lunar surface. Regolith thickness varies immensely depending on the intensity of the meteorite flux since the most recent formation of solid rock materials at a given location on the lunar surface. Components of the regolith are usually highly pulverized and consist of lithic fragments, mineral grains, glass, and agglutinates. The chemical composition is dependent on the nature of the source materials, time of exposure to meteoritic and solar

wind inputs, and the degree of mixing of different materials caused by meteorite bombardment.

Thickness of Regolith

Depth of regolith is a function of both the intensity of the meteorite flux and length of time over which a surface has been exposed to the flux. The youngest mare surfaces which have floors formed by sequences of lava flows with ages of 3.2 billion years have developed only two or three meters of regolith since the last lava flow.⁷ Older mare surfaces covered by lava flows with ages of 3.8 billion years have developed as much as 8 or 10 meters of regolith.⁸ The highlands, however, since their formation about 4.5 billion years ago, have developed at least several hundred meters, or perhaps a few kilometers, of impact-derived debris.^{9,10}

The thickness of regolith on mare surfaces is easily delineated by the observed depth to solid rock units that form flat bottoms or benches in small craters a few tens of meters in diameter. In addition the depth to solid rock was observed along the edge of the Hadley Rille on the Apollo 15 mission.⁷ The depth of highland regolith, however, is more difficult to delineate. There are no obvious flat bottoms or benches to associate with solid rock units. The blocky rimmed craters of the mare are not present in the highlands, again reflecting the lack of shallow rock units in the highlands. A further indication of a thick unconsolidated regolith beneath the highlands is displayed in the pattern of ejecta around craters with 1 to 4 km diameters. In the mare these patterns commonly display circumferential dunes with associated secondary craters reflecting the clustering of ballistic trajectories caused by layers of rock with differing physical properties in the mare. In the highlands the ejecta from these craters form radial patterns of both ridges and secondary craters reflecting the more heterogeneous, poorly-layered, unconsolidated regolith (pers. comm., V. Oberbeck, NASA Ames Res. Ctr.). Seismic data from 3 Apollo landing sites that occur in either highlands or basin ejecta show a 10 to 15m thick surface unit with the very low velocity of 105 to 115 m/sec.⁸ Below this is a unit up to a few hundred meters thick with the relatively low velocity of 250 to 300 m/sec. These two velocities are thought to represent an unconsolidated, porous, fine-grained, upper unit which is underlain by a brecciated ejecta unit that is a bit more consolidated and less porous than the surface units. This is supported particularly well at the Apollo 16 site where photos of the interior of North Ray Crater indicate nearly 250 m thickness of ejecta.⁹ Figure 1 displays the surface stratigraphy at each Apollo landing site.

The depth to bedrock in the highlands is probably on the order of a few kilometers. Highland regolith, therefore, is thicker than mare regolith by at least two orders of magnitude. Seismic data suggests that the first few kilometers of bedrock in both the highlands and mare are highly fractured.

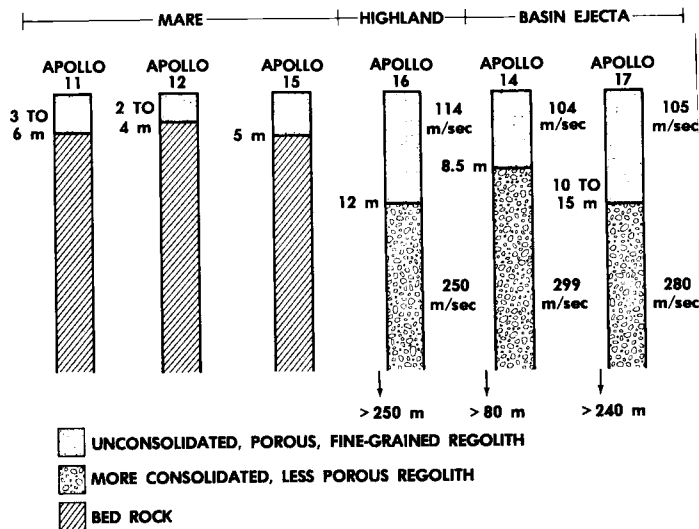


Figure 1: Depth of lunar regolith at the Apollo landing sites. For the Apollo 14, 16, 17 sites, seismic velocities of the upper units were measured and are shown at the side of the columns.

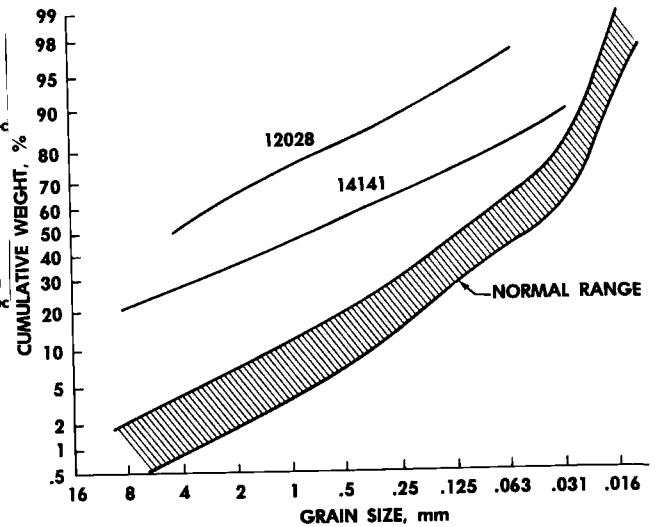


Figure 2: Grain size distribution in lunar soil. Nearly all soils fall in the normal range. Two unusual and extremely coarse-grained soils from the Apollo 12 and 14 sites are shown by solid lines.

Grain-Size Distribution of Regolith

Lunar regolith is a very poorly sorted accumulation of normally angular fragments ranging in size from submicrometer specks to large blocks that are 10's of meters across and usually associated with the rims of fresh craters. Small, cobble-sized rocks are scattered over most surfaces and are particularly prevalent along rays from fresh craters. Most scoops of soil weighing a few kilograms contain several fragments larger than one cm across, but generally 80 wt.% of any soil consists of grains that are less than 250 μm in diameter. The median grain size of most soils is between 60 and 90 μm . In a few rare instances the median sizes range down to 40 μm or up to 500 μm . Figure 2 illustrates cumulative grain size distributions of lunar soils.

Petrography of Regolith

The distribution of lithic, mineral, and glass fragments varies with both grain size and location as set forth in Table 1. One common type of fragment in lunar soil, the agglutinate, is not present in terrestrial surface materials. Agglutinates consist of glass-bonded aggregates of lithic, mineral, and glass fragments. They result primarily from impacts of micrometeorites whose kinetic energy melts part of the target material. On solidification the glass acts as a cement for any unmelted fragments. An important characteristic of agglutinates is their content of iron metal in the form of tiny submicron grains much of which is superparamagnetic. The origin of the iron is attributed generally to reduction of the ferrous iron in sili-

| PETROGRAPHY OF LUNAR SOILS | | | | | | | | | |
|----------------------------|-----------------------------|-----------------------------|----------------------------|---------------------------|-------------------------------|----------------------------|---------------------------|---------------------------|---------------------------|
| in volume % | | | | | | | | | |
| ^a 71061 - MARE | | | | | ^b 64501 - HIGHLAND | | | | |
| | 250 to 500 μm | 150 to 250 μm | 90 to 150 μm | 75 to 90 μm | 45 to 70 μm | 90 to 150 μm | 53 to 74 μm | 44 to 43 μm | 30 to 37 μm |
| Lithic Fragments: | | | | | | | | | |
| Breccia | 7.4 | 7.9 | 5.8 | 6.6 | 2.3 | 21.1 | 26.0 | 36.0 | 24.8 |
| Anorthosite | | | 0.3 | | | 3.0 | | | |
| Basalt | 51.5 | 34.3 | 19.6 | 16.6 | 9.6 | 0.3 | | | |
| Mineral Fragments: | | | | | | | | | |
| Plagioclase | 8.5 | 9.0 | 17.3 | 7.0 | 16.3 | 20.3 | 28.2 | 27.8 | 32.1 |
| Proxene | 10.8 | 17.4 | 21.3 | 26.3 | 21.3 | 0.6 | 1.7 | 1.7 | 6.4 |
| Others | 2.3 | 3.9 | 4.6 | 3.3 | 6.0 | | 0.7 | 0.8 | 0.5 |
| Glass: | | | | | | | | | |
| Colorless | 1.5 | | 1.3 | 1.0 | 1.0 | 1.6 | 6.5 | 8.9 | 10.9 |
| Orange | 0.8 | 4.5 | 6.3 | 5.0 | 7.6 | | | | |
| Other | 6.1 | 10.1 | 14.2 | 16.4 | 19.7 | 1.3 | | | |
| Agglutinates: | 10.0 | 11.8 | 9.3 | 17.3 | 13.0 | 51.6 | 36.8 | 24.8 | 25.4 |

Table 1. Distribution of various fragment types in typical mare and highland soils.

^aFrom Heiken, G. and McKay, D., "Petrography of Apollo 17 Soils," Proc. Lunar Sci. Conf., 5th, 1974, p. 852.

^bFrom Heiken, G., McKay, D. and Fruland, R., "Apollo 16 Soils: Grain Size Analysis and Petrography," Proc. Lunar Sci. Conf., 4th, 1973, p. 257 and Butler, J. Greene, G. and King, E., "Grain Size Frequency Distributions and Modal Analysis of Apollo 16 Fines," Proc. Lunar Sci. Conf., 4th, 1973, p. 275.

cates by the hydrogen derived from the solar wind and residing in the soil. The high temperatures associated with impacts provide the energy to drive the reaction. The magnetic properties of lunar soils are due almost exclusively to metallic iron which generally comprises about 0.5 wt% of the soil composition and consists of about 1/2 as spheres larger than a few μm 's in size and about 1/2 as very fine-grains in agglutinates.^{11,12}

As seen from Table 1 the highland soils contain a higher percentage of plagioclase than the mare soils while the mare soils are enriched in pyroxene, olivine, and basaltic rocks. Glass and agglutinates are common in both. In all soils lithic fragments are most common in the coarser fractions ($>250 \mu\text{m}$) and mineral grains, glass, and agglutinates are more common in finer fractions. Mineral grains increase in abundance with decreasing size fractions. Glass fragments and spheres are particularly prevalent in the very fine fractions where the 5 to 10 μm size range may contain 30 to 50% glass.¹³ Agglutinate contents appear to reach a peak in the 50 to 150 μm size range. These distributions are of particular importance if any separation techniques are to be utilized before chemical or thermal processing of lunar samples commences. Plagioclase, anorthosite, and clear glass can be separated easily in the 150 to 30 μm fraction by magnetic means.¹⁴ The finest-grained material in which solar-wind gases and much metallic iron resides can be separated by sieving. Sieving to separate the larger than 1 cm fraction which is essentially all lithic fragments, should eliminate the most significant heterogeneities and should precede transporting of lunar soil to its processing location.

Chemical Composition of Regolith

Numerous soil samples have been analyzed from six Apollo landing sites including samples from trenches and cores to depths of about three meters. At some sites the samples are distributed over areas of tens of square kilometers. Additionally there are two returned Russian samples, Luna 16 and Luna 20. Photogeologic studies as well as the chemical analyses of the soils suggest at least three major divisions of lunar surface materials: large, circular mare basins, highlands, and ejecta around the large mare basins. The first two form the major and most distinctive areas. Table 2 is a compilation of the average compositions of regolith samples from each of these divisions. A remarkable homogeneity exists among the major components for soils collected from any one of these three divisions at a given landing site. For example at the Apollo 16 site the Al_2O_3 content varies between 26.26 and 28.50% with the average being 27.8%.

From orbiting x-ray and γ -ray spectrometers aboard the Apollo spacecraft, these three divisions are reasonably persistent within the approximately 20% of the lunar surface covered by the measurements which are all within about 25° of the lunar equator.^{15,16} Plans are presently underway to extend this data over the entire lunar surface with a spacecraft in polar orbit about the moon in the early 1980's. In addition to mapping the distribution of such major components as Al, Si, Mg, and K the γ -ray spectrometer could detect the presence of H_2O . The possibility of the presence of water at latitudes above 60° has been predicted because of the presence of permanently shadowed areas which could act as cold traps for the volatile water.¹⁷ About 184,000 km^2 of these areas are predicted above 60° .

Among the major components ($>0.1\%$) there are significant variations between the mare and highland

| | LUNAR REGOLITH COMPOSITIONS | | | | | | | | | |
|---------------------------|-----------------------------|-------|--------|-------|-------|----------|-------|--------------|-------|-------|
| | MARE | | LOW T1 | | | HIGHLAND | | BASIN EJECTA | | |
| | A-11 | A-17 | A-12 | A-15 | L-16 | A-16 | L-20 | A-14 | A-15 | A-17 |
| Al_2O_3 % | 13.78 | 10.97 | 13.71 | 10.32 | 15.51 | 27.18 | 23.07 | 17.41 | 17.54 | 20.60 |
| CaO % | 12.12 | 10.62 | 10.55 | 9.74 | 12.07 | 15.79 | 14.07 | 10.79 | 11.57 | 12.86 |
| Cr_2O_3 % | 0.30 | 0.46 | 0.35 | 0.53 | 0.29 | 0.107 | 0.15 | 0.22 | 0.28 | 0.26 |
| FeO % | 15.76 | 17.53 | 15.41 | 19.75 | 16.41 | 5.18 | 7.35 | 10.36 | 11.58 | 8.59 |
| K_2O % | 0.15 | 0.076 | 0.27 | 0.10 | 0.10 | 0.11 | 0.08 | 0.58 | 0.17 | 0.16 |
| MgO % | 8.17 | 9.62 | 9.91 | 11.29 | 8.79 | 5.84 | 9.26 | 9.47 | 10.41 | 10.29 |
| MnO % | 0.21 | 0.24 | 0.22 | 0.25 | 0.21 | 0.065 | 0.11 | 0.14 | 0.16 | 0.11 |
| Na_2O % | 0.44 | 0.35 | 0.48 | 0.31 | 0.36 | 0.47 | 0.35 | 0.70 | 0.42 | 0.41 |
| P_2O_5 % | 0.12 | 0.07 | 0.31 | 0.11 | 0.14 | 0.12 | 0.11 | 0.50 | 0.16 | 0.14 |
| SiO_2 % | 42.47 | 39.87 | 46.17 | 46.20 | 43.96 | 45.09 | 44.95 | 48.08 | 46.59 | 45.08 |
| TlO_2 % | 7.67 | 9.42 | 3.07 | 2.16 | 3.53 | 0.56 | 0.49 | 1.70 | 1.32 | 1.62 |
| Al % | 7.29 | 5.80 | 7.25 | 5.46 | 8.21 | 14.38 | 12.20 | 9.21 | 9.28 | 10.90 |
| Ca % | 8.66 | 7.59 | 7.54 | 6.96 | 8.63 | 11.29 | 10.06 | 7.71 | 6.27 | 9.19 |
| Cr % | .21 | .31 | .24 | .36 | .20 | .07 | .10 | .15 | .19 | .18 |
| Fe % | 12.25 | 13.63 | 11.98 | 15.35 | 12.76 | 4.03 | 5.71 | 10.36 | 9.00 | 6.68 |
| K % | .12 | .063 | .22 | .08 | .08 | .09 | .066 | .46 | .14 | .13 |
| Mg % | 4.93 | 5.80 | 5.98 | 6.81 | 5.30 | 3.52 | 5.59 | 5.71 | 6.28 | 6.21 |
| Mn % | .16 | .19 | .17 | .19 | .16 | .050 | .085 | .11 | .12 | .085 |
| Na % | .33 | .26 | .36 | .23 | .27 | .35 | .26 | .52 | .31 | .30 |
| O % | 41.6 | 39.7 | 42.3 | 41.3 | 41.6 | 44.6 | 44.6 | 43.8 | 43.8 | 42.2 |
| P % | .05 | .03 | .14 | .05 | .06 | .05 | .05 | .22 | .07 | .06 |
| S % | .12 | .13 | .10 | .063 | .21 | .064 | .08 | .088 | .08 | .06 |
| Si % | 19.84 | 18.63 | 21.57 | 21.58 | 20.54 | 21.07 | 21.00 | 22.46 | 21.77 | 21.06 |
| Ti % | 4.60 | 5.65 | 1.84 | 1.29 | 2.11 | .34 | .29 | 1.02 | .79 | .97 |
| Ag ppb | 9.0 | 9.8 | 62.0 | 50.0 | 95.0 | 9.6 | 16.2 | 17.5 | 56.0 | 6.5 |
| Ar ppm | 1.0 | 1.2 | 0.3 | 0.7 | | 1.2 | | 1.0 | | |
| As ppm | 0.32 | | 0.082 | 0.010 | 0.41 | 0.14 | 0.28 | 0.066 | | |
| Au ppb | 3.7 | 2.5 | 2.5 | 2.11 | 2.5 | 8.47 | 4.93 | 6.7 | 3.3 | 4.9 |
| B ppm | 3.5 | 2.0 | 9.3 | | 4.3 | 5.9 | 39.0 | 19.0 | | |
| Ba ppm | 140. | 85.7 | 413. | 122. | 215. | 127.3 | 89.6 | 767.5 | 279. | 190. |
| Be ppm | 2.0 | | 5.0 | 1.31 | 2.2 | 1.2 | | 5.5 | 2.8 | |
| Bi ppb | 1.5 | 7.7 | 1.5 | 0.36 | 4.9 | 1.8 | 2.7 | 1.7 | 0.17 | |
| Br ppm | 0.239 | 0.093 | 0.165 | | 0.21 | 0.217 | 0.13 | 0.41 | 0.06 | |
| C ppm | 135. | 82. | 104. | 95. | | 106.5 | | 130. | 125. | 155. |
| Cd ppm | 0.045 | 0.032 | 0.046 | 0.062 | 0.80 | 0.097 | 0.048 | 0.181 | 0.042 | 0.04 |
| Ce ppm | 50.0 | 25.3 | 104.0 | 31.4 | 33.4 | 30.3 | 20.5 | 185.0 | 54.0 | 46.0 |
| Cl ppm | 30.2 | 5.7 | 31.0 | 7.6 | 53.5 | 20.9 | 13.0 | 44.0 | 5.9 | |
| Co ppm | 32.0 | 35.0 | 43.0 | 54.4 | 37.0 | 25.3 | 40.5 | 35.8 | 42.0 | 33.0 |
| Cs ppm | 0.18 | 0.30 | 0.30 | 0.23 | 0.95 | 0.11 | 0.11 | 0.63 | 0.19 | 0.18 |
| Cu ppm | 11.5 | 11.0 | 10.3 | 8.2 | 31.0 | 8.26 | 19.0 | 11.1 | 7.9 | 6.4 |
| Dy ppm | 20.2 | 12.2 | 24.6 | 8.6 | 10.9 | 6.8 | 5.0 | 39.0 | 13.6 | 11.0 |
| Er ppm | 11.5 | 7.90 | 15.35 | 5.13 | 6.3 | 4.59 | 2.5 | 23.5 | 7.86 | 6.5 |
| Eu ppm | 2.0 | 1.66 | 1.9 | 1.01 | 2.3 | 1.23 | 0.98 | 2.64 | 1.30 | 1.35 |
| F ppm | 278. | | 132. | 45. | 242. | 72. | 37. | 219. | 60. | |
| Ga ppm | 4.3 | 7.5 | 4.3 | 4.43 | 4.4 | 4.5 | 3.7 | 6.8 | 3.6 | 4.7 |
| Gd ppm | 16.3 | 11.4 | 25.7 | 8.1 | 9.8 | 6.7 | 3.06 | 34.8 | 11.74 | 10.07 |
| Ge ppm | 1.0 | 0.198 | 0.32 | 0.17 | 1.44 | 0.6 | 0.46 | 0.70 | 0.42 | |
| H ppm | 51.0 | 59.6 | 45.0 | 63.6 | | 56.0 | | 79.6 | 52.0 | 98.0 |
| He ppm | 60.0 | 36.0 | 10.0 | 8.0 | | 6.0 | | 8.0 | | |
| Hf ppm | 8.9 | 7.3 | 12.7 | 5.2 | 4.76 | 3.9 | 2.9 | 22.2 | 7.6 | 5.5 |
| Hg ppm | 0.015 | | 0.023 | | | 0.004 | | | | |
| Ho ppm | 6.4 | | 8.3 | 1.7 | 2.5 | 1.50 | 0.88 | 7.8 | 3.3 | |
| I ppb | 2.0 | | | | | 5.6 | 12.0 | | 35.0 | |
| In ppb | 2.4 | | 90.0 | 3.4 | 35.6 | 31.0 | 19.0 | 89.0 | 7.6 | 3.4 |
| Ir ppb | 7.8 | 5.4 | 5.6 | 3.1 | 9.7 | 12.4 | 9.5 | 12.4 | 8.3 | 8.8 |
| La ppm | 17.3 | 7.32 | 38.8 | 11.3 | 11.5 | 11.7 | 7.6 | 69.4 | 24.0 | 16.9 |
| Li ppm | 16.5 | 9.77 | 19.5 | 9.09 | 9.7 | 7.4 | 5.7 | 29.8 | 10.8 | 11.7 |
| Lu ppm | 1.6 | 1.03 | 1.93 | 0.72 | 0.84 | 0.59 | 0.40 | 3.10 | 0.98 | 0.88 |
| Mo ppm | 0.70 | | 0.34 | | | 0.34 | | | | |
| N ppm | 119. | 60. | 84. | 80. | 134. | 89. | 107 | 92. | 190. | 81. |
| Nb ppm | 15.8 | 19.1 | 34.0 | 13.0 | 15.9 | 12.8 | 12.0 | 56.0 | 16.0 | 18.0 |
| Nd ppm | 42.6 | 23.0 | 75.6 | 23.0 | 26.9 | 19.3 | 10.8 | 105.0 | 35.0 | 27.6 |
| Ne ppm | 5.0 | 2.0 | 2.0 | 2.0 | | 1.0 | | 2.0 | | |

^aData compiled from the Data Base Compilation of the Lunar Sample Curator, Johnson Space Center, Houston

| | MARE | | | | | HIGHLAND | | BASIN EJECTA | | |
|--------|---------|-------|--------|-------|-------|----------|-------|--------------|-------|-------|
| | HIGH T1 | | LOW T1 | | | A-16 | L-20 | A-14 | A-15 | A-17 |
| | A-11 | A-17 | A-12 | A-15 | L-16 | | | | | |
| Ni ppm | 206. | 131. | 189. | 146. | 174. | 345. | 208. | 321. | 282. | 286. |
| Os ppb | 14.0 | | 6.0 | 1.79 | 30.0 | 22.0 | | | | |
| Pb ppm | 2.9 | 0.80 | 4.8 | 1.033 | 6.0 | 2.58 | 1.15 | 10.02 | 2.5 | 1.922 |
| Pd ppb | 21.0 | | 9.7 | 6.2 | | 24.0 | | 50.0 | | |
| Pr ppm | 7.7 | | 10.1 | 3.8 | | 4.97 | 4.0 | 23.0 | | |
| Rb ppm | 3.0 | 1.2 | 7.28 | 2.70 | 1.85 | 2.48 | 1.65 | 15.25 | 5.0 | 4.21 |
| Re ppb | 5.26 | 0.47 | 0.34 | 0.39 | 0.36 | 0.82 | 3.19 | 1.15 | | |
| Rh ppm | 0.1 | | 0.4 | | 0.077 | | | | | |
| Ru ppm | 0.6 | | 0.047 | | 0.046 | 0.010 | | | | |
| Sb ppb | 4.1 | 25.4 | 47.0 | 30.0 | 3.8 | 9.7 | 5.7 | 3.4 | | 26.0 |
| Sc ppm | 62.8 | 65.0 | 39.2 | 37.1 | 39.9 | 8.9 | 17.0 | 21.9 | 22.0 | 18.0 |
| Se ppm | 0.39 | .27 | 0.30 | 0.18 | 0.39 | 0.24 | 0.30 | 0.031 | | 0.23 |
| Sm ppm | 11.7 | 8.0 | 20.3 | 5.85 | 8.8 | 5.38 | 3.39 | 30.9 | 9.6 | 8.1 |
| Sr ppm | 0.7 | | 0.3 | | 1.7 | 0.22 | 0.8 | | | |
| Ta ppm | 193.0 | 166.0 | 138.9 | 104.2 | 234.0 | 168.0 | 140.8 | 183.8 | 152.0 | 150.0 |
| Ta ppm | 1.5 | | 1.58 | 0.55 | 1.4 | 0.50 | 0.50 | 4.1 | 1.05 | 0.87 |
| Tb ppm | 3.3 | 2.63 | 4.07 | 1.4 | 1.5 | 1.07 | 0.80 | 6.4 | 4.2 | 1.72 |
| Te ppm | 0.07 | 0.01 | 0.05 | | 0.088 | 0.023 | 0.051 | 0.031 | | |
| Th ppm | 2.24 | 0.82 | 6.63 | 1.76 | 1.07 | 1.87 | 1.44 | 13.5 | 4.15 | 3.01 |
| Tl ppb | 2.1 | 1.4 | 2.0 | 0.94 | 1.6 | 7.7 | 6.2 | 22.0 | | 2.4 |
| Tm ppm | 1.5 | | 2.02 | | 0.73 | 0.67 | 0.41 | 3.9 | | |
| U ppm | 1.37 | 0.26 | 1.61 | 0.483 | 0.300 | 0.52 | 0.45 | 3.48 | 0.99 | 0.90 |
| V ppm | 66. | 128. | 110. | 191. | 73.5 | 25.5 | 38. | 49. | 84. | 52. |
| W ppm | 0.24 | 0.14 | 0.74 | 0.31 | | 0.31 | | 1.9 | | 0.52 |
| Y ppm | 107. | 74. | 145. | 47. | 48. | 39.3 | 49. | 242. | 73. | 64. |
| Yb ppm | 10.6 | 7.48 | 13.7 | 4.53 | 5.59 | 3.86 | 2.40 | 22.7 | 7.3 | 6.15 |
| Zn ppm | 23.0 | 49.0 | 6.3 | 12.8 | 25.0 | 24.0 | 34.1 | 28.0 | 14.5 | 20.0 |
| Zr ppm | 331. | 236. | 503. | 175. | 308. | 163.8 | 192. | 842. | 278. | 262. |

Table 2. Compilation of average composition of lunar soils for 80 elements. Major elements (>0.1%) are reported first as both the usual oxide notation and elements.

regoliths. The highlands are enriched in Al and Ca while the mare are enriched in Fe, Cr, Mn, and Ti. Furthermore, the mare areas display significant variations in Ti content. Basin ejecta are intermediate in composition except for a few elements such as K and P which tend to be highest in the ejecta. Data from orbital spectrometers extend this pattern over most of the moon's equatorial region. In fact, the highland areas on the far side appear to have a higher Al content than the Apollo 16 site.

Many of the minor components in the regolith are enriched by factors of 10^2 to 10^3 over their content in fragments of bedrock.¹⁸ These components include Ni, Co, Au, Ir and others that are derived mainly from meteoritic input to the lunar surface. Thus any refinement processes to obtain these metals should be confined to surface materials; although future data from chemical mapping by orbital spectrometers might modify this conclusion.

Iron is present as both Fe^{++} and metallic iron, Fe^0 . The Fe^0 is derived largely from the reduction of Fe^{++} by the H_2 in the soils. Fe^0 generally comprises 0.5 to 0.6 weight percent of lunar soils, and between 0.15 and 0.20% is in the form of metallic fragments greater than 100 μm across.¹² The remainder is finer grained, much of it being superparamagnetic and ranging down to 50A, or less, in size.

Among the minor components only Ba, Ni, Sr and Zr are present consistently in concentrations of 100's of parts per million. A few others: Ce, Ca, F, Nb, Nd, Sc, V, Y, and Zn are present consistently in concentrations of 10's of parts per million. The remainder are present in even lower concentrations. In fact, many such as Ag, Au, In, Ir, and Re are present in the range of only 1 to 10 parts per billion.

Many components that are derived largely from

the solar wind are concentrated in the finer-grained size fractions at the surfaces of grains. These include C, N, Ar, H, He, Ne, Kr, and Xe and are easily released from the soils in gases formed during heating. Sulfur, though not derived from the solar wind, is also released as gases during heating. About 25% of the carbon is indigenous to the rocks from which the soil was derived and is not released as a gas until very high temperatures well above the melting point of the soil.^{19,20}

Processing of Lunar Regolith

Fabrication of large structures in space such as power satellites, space colonies or industrial facilities will require large quantities of structural metals, glass and ceramic materials. Power satellites may require silicon for photovoltaic cells. All space operations beyond low earth orbit would benefit greatly from a source of oxygen in space. If these products can be refined economically from lunar surface materials, the cost of space operations can be reduced significantly. To produce these products, with the exception of ceramic materials, requires considerable processing. The following sections discuss potential refinement processes and feasibilities for production of metals with their by-products of silicon and oxygen, glasses, ceramics and gases.

Metals

The most readily accessible source of metal consists of fragments of metallic iron that comprise between 0.15 and 0.20% by weight of the lunar soil. In addition to iron, this metal contains about 5% Ni and 0.2% Co. During magnetic separation, this metal is easily separated from the soil in low magnetic fields. This source of metal occurs in quite low concentrations, and provides only iron. In order to provide a more comprehensive processing of lunar soils to supply iron, aluminum, silicon, magnesium and perhaps other metals, such as titanium, chromium and manganese while producing oxygen as a by-product, a reduction and separation process is necessary.

Potential approaches include aqueous solution, halogen, and direct electrolysis processes, but carbothermic and silicothermic processes appear most promising from the standpoint of equipment-mass, volume, and foundation in current practice. One such process has been designed and evaluated. Figure 3 displays the major components of the system. Remaining uncertainties make it only one of a family of closely related practices.

This system requires very low consumption of materials lifted from earth. It makes extensive use of simple or tested techniques, and has high product output per unit of equipment mass. The only process-chemicals brought from earth are carbon and hydrogen. Both are indefinitely recycled and should have economically negligible loss rates. Virtually all of the components used are either simple enough or similar enough to tested pilot plant and industrial facilities to permit analysis and weight estimation. The processes must be optimized for the composition of lunar soil.

The central reaction in this system, a carbothermic reduction capable of reducing the oxygen-bound elements: silicon, aluminum, calcium, manganese, chromium, titanium and magnesium, occurs in the box labeled "Carbothermic Reduction of Al, Si, Mg, Ca." Because of possible limitations in metal separation, a prior reduction and separation of iron is required in the box labeled "Silicothermic Reduction, Fe^0 ." Because the carbothermic reaction

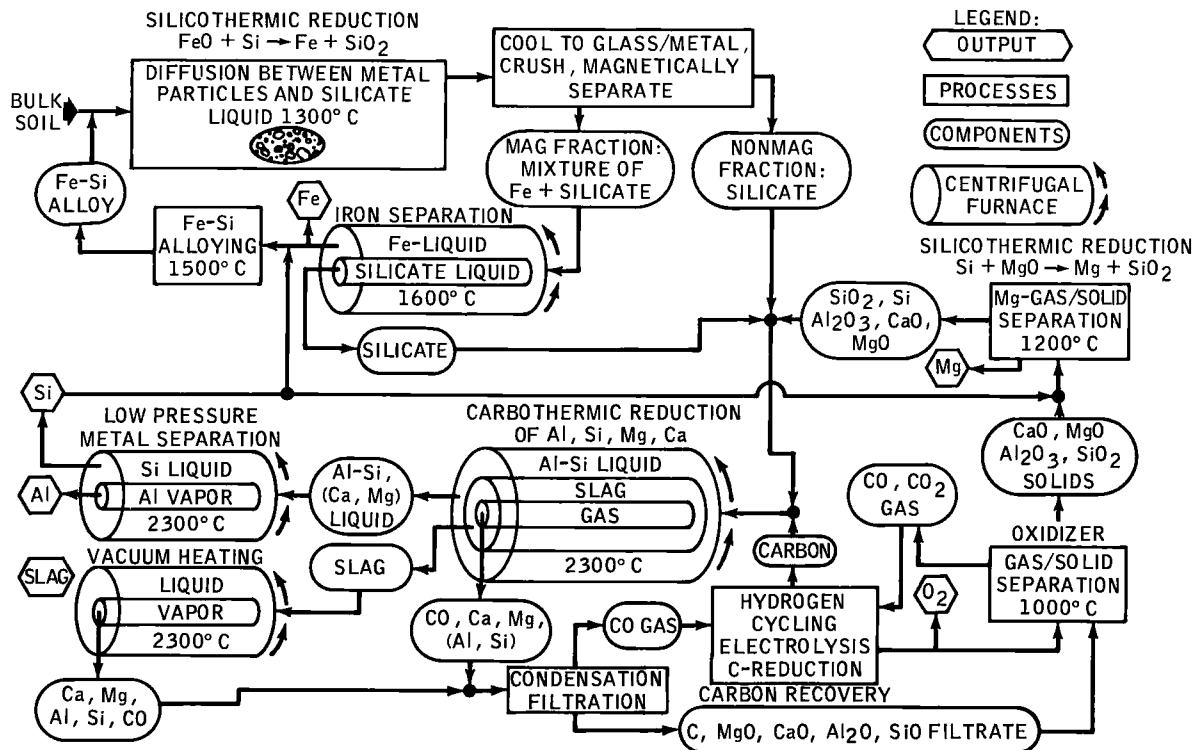
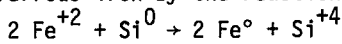


Figure 3: Proposed flow diagram for processing of lunar soils. Temperatures shown are approximate. Components shown in flowstreams are not necessarily the molecular species that may be present.

produces a mixture of silicon, aluminum and other metals, a "Low Pressure Metal Separation" is shown. Carbon is recovered from carbon monoxide in the "Carbon Recovery" box.

Iron Reduction

The goal of this subsystem is to reduce substantially all of the ferrous iron of the incoming soil to metal, and to produce this metal in separable grains. One method is the introduction of ferrosilicon particles which reduce and scavenge the ferrous iron by the reaction:



which thermodynamically is very favorable. The free energy of the reaction is -47.4 K cal per mole of silicon at 1300°C, the approximate temperature of the reaction.

The ferrosilicon particles may be formed by melting and combining iron and silicon from their respective product streams to produce a mixture, which is then solidified by means of melt-spinning²¹ to produce a ferro-silicon alloy. The melt-spinning process is required for this low-Si metal to produce the small particle sizes of ~50 µm which are necessary for this reduction reaction.

Rock or soil ground to sub-200 µm in a vibratory ball mill is mixed with the ferro-silicon in a low-power, high throughput ball mill. The ball mills operate under zero-gravity conditions. Feed and fines removal is accomplished by gas entrainment through a bellows attachment. Similar vibratory ball mills are used throughout the entire system for size reduction. The product stream now consists of ~50 µm ferro-silicon particles dispersed in a matrix of rock particles. This mixture is charged to a furnace where a silicothermic reaction occurs.

In this reaction silicon diffuses from the ferro-silicon phase to the surrounding silicate material where it reduces the iron oxide liberating metallic iron. The most likely temperature for this

reaction seems to be between the liquidus of the silicate phase (1200 to 1250°C for mare soils, and 1300 to 1350°C for highland soils),²² and the solidus of the ferrosilicon phase (~1350 for 8% Si).²³ This temperature should keep the diffusivity of the Fe⁺² in the silicate reasonably high, and the diffusivity of Si in the ferro-silicon low. If one assumes that the characteristic time for diffusion of Fe⁺² into the 50 µm metal phase is short compared to the characteristic time for Si diffusion out of the metal phase (and hence the characteristic time for iron reduction), then the near-equilibrium path of iron diffusing into the 50 µm iron particles will be followed, as opposed to nucleation and precipitation of new, colloidal iron particles. The major uncertainty in this reaction is whether the reduced iron precipitates in the silicate phase, or whether it diffuses to the thermodynamically-preferred location within the comparatively large (~50 µm) iron particles left after the ferro-silicon reacts. Diffusion data was not found in a search of the literature for industrial or experimental examples of this reduction technique.

If precipitation of unrecoverable small Fe⁰ particles occurs, a reasonable variant process should be possible. If a substantial amount (~1% by weight) of the iron is left as silicate-soluble Fe⁺² (through control of silicon additions), coarsening of Fe⁰ grain size will occur as the large 50 µm "seed" grains grow at the expense of small grains. This has been observed in glassy lunar silicates, even under solid state conditions.^{24,25} Apparently, by a fairly slow process of growth from a small colloidal population, iron grains of up to 5 µm have formed under lunar conditions.

If either solution to the accomplishment of large grain-size proves satisfactory, the product of the furnace will be molten, low-iron silicates, and ~50 µm iron particles. These are passed to a cooler, whose product is glassy silicate with embedded iron particles.

This material is passed to a ball mill, where

it is ground to a particle size comparable to that of the iron grains, but not overground enough to allow smearing of silicate into the more malleable metals. This should produce two types of grains: those containing no metallic iron, and those consisting of metallic iron with adhering silicate. A magnetic separator is used to separate the two grain types.

The metal-rich fraction is melted in a centrifugal furnace (Iron Separation of Fig. 3), where adhering silicates are melted and float off as a slag, much as in terrestrial steel making. Metal enrichment in the magnetic separation was performed to make iron the continuous phase on melting, as its low viscosity compared to molten silicates greatly enhances the speed of the density separation.

The iron is tapped from the outer layer. Some is sent to the "alloying" stage, the rest may be cast as product ingots for later conversion to steel. Any Ni and Co present in the initial soil should be present in the iron metal. The silicate is tapped from the inner layer and, together with silicates from the magnetic separator, is passed to the Carbothermic Reduction sub-system of Figure 3.

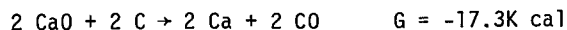
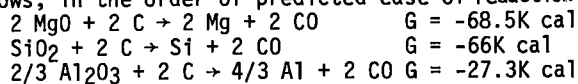
If neither of the solid state diffusion reactions proves to be feasible for large scale reduction and separation of iron, an alternative method may be used at higher temperatures where both the ferrosilicon alloy and the silicate occur as melts. Russian workers have studied this reduction reaction at 1500 and 1600°C with both 25 and 45% Si in the alloy and have provided data on reaction rates for iron reduction in a tubular reactor.²⁶ For these ferrosilicon compositions the phase is in an inter-metallic state and fine particle size can be achieved by crushing in a ball mill rather than by melt spinning. Assuming first order kinetics at 1500° with no stirring, the reaction rates indicate that 80% reduction would occur in about 20 hours. Mechanical mixing of the two melts was found to increase the reaction rate by factors of 4 to 5. An increase in temperature further increased the rate.

The main uncertainty with this reaction is the location of the reduced iron. If it enters the Fe-Si alloy, separation of iron could be accomplished through oxidation of any remaining Si to SiO₂ at about 1600°C, at which temperature the iron should not oxidize. If it remains in the silicate melt as very fine blebs it will be necessary to devise a technique to agglomerate the blebs. In either case the iron can then be separated by the same techniques as outlined for the previous process.

Aluminum, Silicon, Calcium and Magnesium Reduction

In this subsystem incoming low-iron silicates containing primarily Si⁴⁺, Ca⁺⁺, Mg⁺⁺, Al³⁺ and possibly Ti⁴⁺ if derived from mare soils, and lesser amounts of other ions such as Mn⁺⁺ and Cr³⁺ are mixed with carbon from the carbon recovery section, then charged to a centrifugal furnace, where they melt and are reduced by the carbon. The furnace was modeled after a WW II pilot plant.²⁷ The major difference is the presence of silicates containing Mg⁺⁺ and Ca⁺⁺ in the lunar soil feed stock rather than nearly pure Al₂O₃ and SiO₂ as in the pilot plant study. The furnace operated at about 2,300°C.

At 2,300°C the thermodynamic data is highly favorable for the carbothermic reduction of Mg, Si, Al and Ca. The free energies at 2,300°C are as follows, in the order of predicted ease of reduction:



Despite the compositional difference between lunar soil and the feedstock of the pilot plant, the most important reactions seem in little doubt. Aluminum and silicon ions are expected to reduce to a Si-Al melt, as they did in the pilot plant study.

Major questions exist regarding the extent of reduction of Ca, Mg, Ti, Mn and Cr and their distribution between metal, slag and vapor phases. The formation of carbides and suboxides in these complicated systems requires detailed study of the proper temperatures and proportions of carbon to silicate in the feedstock.

Even in a simple system involving carbothermic reduction of Al₂O₃, it was found that a two-step operation was necessary to overcome the formation of carbides.²⁸ First, a rich carbon mixture with 85:15 of C: Al₂O₃ was heated to about 1900°C to start the reaction. Then a leaner mixture of C was added with 65:35 proportions and heated to overcome the carbide formation. The formation of Al occurred between 2,000° and 2,050°C.

The pilot plant operation with Al₂O₃ and SiO₂ showed that the formation of carbides made it impossible to obtain a melt of Al and Si below temperatures of 2,000°C.²⁷ It was necessary to maintain the ratio of carbon to oxide at 70 to 75% of the stoichiometric value for complete reduction to avoid carbide formation even at the 2,300°C operating condition. Also, the compositions of the alloys remained within the range of 25 to 70% Al. The few percent of Ti⁴⁺ in the ore was also reduced and occurred in the alloy. The yields were found to be 65% of the Si and 90% of the Al during continuous operations, producing about 2,000 lbs. per day. Material balance calculations indicated that several percent each of Al and Si were lost through vaporization, probably as Al₂O and SiO.

Further addition of magnesium and calcium should provide further complications during the carbothermic reduction, but there have been no studies of this system. It is known that the reduction of a mixture of CaO and SiO₂ by carbon proceeds first by the formation of SiC.²⁹ Then, at temperatures greater than 2,000°C, the reduction of CaO to Ca occurs with the accompanying formation of calcium silicide. This suggests that most of the Ca will join Si and Al in the melt stream, rather than vaporizing into the gas stream. The reduction of MgO by carbon at 2,000°C results in Mg gas.³⁰ In the presence of Si and Al during silicothermic reduction, the Mg should again occur as a vapor because the vapor pressure of Mg at 2,300°C is several orders of magnitude greater than Al and Si and over an order of magnitude greater than Ca. Thus the Mg should join the vapor stream rather than the melt.

A major problem to consider during the carbothermic reduction process is the formation of carbides. One means of overcoming carbide formation is to raise the temperature of the reaction. The pilot plant studies, however, showed volatile losses of some Al₂O and SiO at 2,300°C, suggesting that higher temperatures would cause even greater volatilization.²⁷ Thus, other means must be found to control carbide formation.

The product flowstreams of the carbothermic reduction unit include a metal stream consisting primarily of Si and Al, and probably Ca (also Ti, if derived from mare soil) with other nonvolatile metallic components; a slag stream consisting possibly of silicates and oxides; and a vapor stream consisting of CO, Mg, SiO, aluminum compounds and possibly some Ca.

The metal stream is passed to a Low Pressure

Metal Separation System, whose minimum goal is to recover substantially all of the aluminum in metallurgical grade. A further goal might be the recovery of silicon for further purification to solar-cell grade, or the recovery of the other metals, such as Cr, Mn, and Ti, for alloying or other purposes.

The first step in the metal separation is the removal of Ca by distillation at 1,400°C and 10⁻³ Torr. Under these conditions, the distillation of alloys having the composition Al₅₃Si₂₅Ca₂₂ produces over 96% extraction of Ca.³¹ The distillate contains 1.6% Al and 0.17% Si.

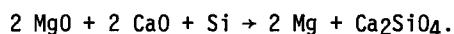
The minimum goal now may be met in several ways. The one illustrated represents a distillation/fractional solidification approach, relying on experimental data on the distillation of Al-Si alloys.³² The distillation stages, however, require a fairly simple but undemonstrated piece of high temperature equipment.³³ Other options exist and have been demonstrated on a pilot-plant scale. They include liquid-liquid extraction with molten zinc, and chemical volatilization processes.³² Purification of the silicon and separation of the other metals from it and each other deserve study, but promise to be more complex.

The slag stream is heated in near-vacuum to drive off any contained carbon (carbides, etc.) as CO. The vapor stream from the vacuum heating is added to the vapor stream from the Carbothermic Reduction (see Fig. 3). The resulting stream is cooled and the condensates are filtered. On cooling, experience shows that Ca and Mg will back-react with CO to form MgO, CaO, and C as solids.³⁰ These, and other solids, are trapped at the filter while the CO gas is passed to carbon recovery.

The filtered solids are oxidized primarily to remove the carbon as CO and CO₂, and prevents another reaction-volatilization-backreaction sequence in the next reactor. Also, any other components that were not oxidized may now be oxidized to simplify the silicothermic reduction of magnesium.

The oxides from the oxidizer are fed to a silicothermic reduction furnace for the production of Mg. Reduction of MgO by Si is one of the major commercial processes for the production of magnesium.³⁴ In the solid state process, prior to the reduction reaction, the silicon and the products from the oxidizer should be milled to about 75 μm and pressed into large briquettes at 2 tons/in.² to increase the surface area involved in the diffusion of Si into the oxides. To allow for an adequate diffusion rate of Mg vapor out of the system, the briquettes are crushed to fragments about 1/2 by 3/8". The reactants are then heated to about 1,200°C to allow the solid-solid reaction to occur. The yield is about 80% in 30 minutes.³⁴ The Mg vapor can be removed by either pumping it off or passing an inert carrier gas over the reactants.

The presence of SiO₂ from the oxidizer or from the oxidation of Si during the reduction reaction can be a problem in this process, as it reacts with MgO to form Mg₂SiO₄. This may be overcome by the presence of sufficient CaO in the reactants to produce the reaction:



This is the usual reaction for the commercial production of Mg. The CaO, if not already present in the oxidizer, can be produced by feeding Ca from the metals separation into the oxidizer to produce CaO before being fed to the furnace for Mg production. A ratio of CaO + MgO : Si of 1.5 : 1 produces a

yield of 86% of the Mg.³⁴ Additions of SiO₂ decrease the yield unless more CaO is added to produce Ca₂SiO₄. Addition of 10% Al₂O₃ decreases the yield by about 10%. As more SiO₂ and Al₂O₃ are added, the yield goes down even more. Presumably, the increased content of non-reacting products slows the diffusion rate in the solid-solid reaction. Thus, the production of Mg should present no problem unless vaporization of Al and Si compounds is extensive during the carbothermic reduction reaction. Proven alternative processes involve silicothermic reduction at higher temperatures in the molten state.³⁵

Mg is condensed from a vapor as a reasonably pure metal, but may be further distilled if need be. Other materials, from the Mg reduction (unreacted silicon, oxides, etc.) are returned to the carbothermic unit, where they have another chance to react. However, it may be of little use to recirculate the remains of this reduction process if it contains nearly all Ca₂SiO₄, which is of no further use in the system unless it is converted to CaO and recycled through the Mg reduction again to react with SiO₂.

An alternative procedure for the production of aluminum and silicon is the processing of the mineral plagioclase which comprises about 20 to 25% of lunar highlands soil. Highland plagioclase is nearly pure CaAl₂Si₂O₈ and can be easily separated to about 99% purity. Such a feed stock to the carbothermic reactor would simplify the production of large quantities of pure Al and Si if so desired.

Carbon Recovery

In this subsystem CO is first reacted with hydrogen in a catalytic reactor to produce water, methane and perhaps some other hydrocarbons. This reaction and its relatives have been used industrially in the petrochemical industry for many years.³⁶ It requires a catalyst, but this may be as simple as iron oxide mill scale.

The methane, water and any remaining hydrogen are then dried by removal of most of the water in a condenser. The water is electrolysed in one of several industrial water electrolysis cells. Hydrogen is returned to the methane reactor; oxygen is a product-flowstream except for some that is used in oxidation reactions elsewhere in the system.

The methane is passed over a checkerwork of heated bricks, as in many industrial plants for the production of thermal carbon black from natural gas.³⁷ The methane decomposes to C and H₂, and the carbon exits the furnace as dust mixed with hydrogen (both are decomposition products). Means (possibly oxidation) must be designed to limit buildup of the remaining carbon on the checkerwork; terrestrially this is done by combustion during the heating phase, but it would be advantageous to avoid this in the present application, as the mechanical form of the carbon is nearly irrelevant to its value.

Glass and Ceramics

Three products can be obtained by heating directly the lunar soil: glasses, sintered materials, and cast-basalt objects. Each of these requires melting a portion (sintering) or all of the material. Nature has demonstrated the production of glasses (agglutinates), sintered rocks (breccias), and cast rocks (basalts) from lunar soils in the lunar environment. Rocks and glasses derived directly from lunar materials may be significantly different in several physical properties than the rocks and glasses formed on an industrial scale from approximately comparable terrestrial raw materials due to the complete absence of lunar water. Compared

to terrestrial glasses the lunar-derived glasses should be stronger and considerably more resistant to long-term mechanical fatigue due to surface scratches because there is no water acting on surface cracks to weaken the surface energy of the glass.³⁸ Conversely, rocks formed either by sintering of the soil or casting of molten soil may be weaker against dynamic loads than corresponding rocks formed on earth. Lunar soils and rocks retain vibratory energy (a few Hz to KHz range) 100 to 1000 times better than terrestrial rocks.³⁹

Glass

Production of clear glass would result from separation of the mineral, plagioclase, from lunar highland soil. The mineral is nearly pure $\text{CaAl}_2\text{Si}_2\text{O}_8$, with about 0.5% Na_2O and less than 0.1% FeO , and would require no processing to remove iron. Plagioclase from mare soils contains considerably more Na_2O and up to 1.0% FeO , and would require further processing to remove iron. Plagioclase has the lowest magnetic susceptibility of lunar soil components, and can be separated to about 99% purity as the non-magnetic fraction in a high magnetic field.¹⁴ It melts at temperatures of almost 1550°C, has high viscosity, low thermal expansion, and high strength, and can be used at relatively high temperatures.

A second alternative for the production of clear glass involves oxidation of the Si produced during metals processing. The resulting SiO_2 has a melting temperature in excess of 1710°C. The purity of Si from the metals processing is not known in detail, and will require additional laboratory research. Further processing of the Si may be necessary to obtain the desired purity for clear glass.

Production of clear glass fibers for fiberglass products could utilize either the plagioclase or silica sources mentioned earlier. Opaque fibers could be produced by direct melting of lunar soil. The melting temperature of mare soils is about 1200 to 1250°C and that of the highland soils is about 1300 to 1350°C.

Utilization of sintered materials for structural elements, possibly filters or other products compatible with hot pressing techniques derived from ceramics⁴² should receive attention. However, it should also be noted that sintering of lunar material requires the same order of magnitude of energy (≈ 500 joules/gr) to heat (specific heat ≈ 0.8 joules/gr-°K) as to melt (heat of fusion ≈ 40 -60 joules/gr) the material and is very energy intensive. Almost as much energy is required to melt lunar soil per unit of mass as is required to eject it from the moon.

Sintering

If an aggregate of fine-grained particles is heated to a high enough temperature, material is transferred from the free surfaces of individual grains to the area of contact between touching grains. This is sintering and the driving energy is the surface-free energy. As necks of the transported material develop between grains, the total free surface of the grains is reduced. Bulk diffusion, vapor transport, or viscous flow describe the possible material-dependent transport mechanisms. For all three mechanisms the rate of bulk sintering increases with decreasing grain size. It is well documented that the glass in lunar soils dominates the sintering of lunar soil during formation of breccias.⁴⁰ Stress-free sintering of lunar materials in vacuum is straightforward. The soil is heated to

approximately 800-900°C and maintained at that temperature range for a few seconds for Apollo 14 soil to 10's of minutes for Apollo 16 highlands soil and then quickly cooled at rates of 0.1° K/min to 5°K/minute. Increasing the temperature slightly and/or applying pressure up to 500 bars quickens the sintering process, produces higher bulk densities (i.e., lower porosity), and leaves a higher fraction of glass. The maria soils are easier to sinter (low temperature and less time) than highland soils due to the higher content of impact-produced glass in the soil.

Breccias dominate the population of rocks on the lunar surface. They range from extremely friable or weak clods to rocks which are difficult to break by pounding with a hammer. Warner⁴¹ has classified many of the properties of the Apollo 14 breccias versus bulk density and reported systematic variations in gas content, density of included rocks, and other parameters. Unfortunately, there has been no comparable systematic study of the mechanical properties of a complete range of rocks, either breccias or basalts. Thus, complete information on Young's modulus, limiting stress, dynamic stress limits and other features are not available.

Cast Basalt

Industrial development of products formed by casting of molten-silicates has been a vigorous activity in Europe for many years.⁴³ The products include not only obvious things such as tiles, building segments, pipes (3-10 cm diameter and 1 to 1.5 meters long) and dishes but also pump casings, hydrocyclones, acid and alkali resistant containers, linings for furnaces, binders to form polishing tools containing corundum or silicon carbide grains, molds (drawing dies) for use in glass making, and many other items. In general, these artificial "stones" are characterized by good abrasion resistance (.06-.08 cm gr/cm²), high chemical resistance, high softening temperatures, higher thermal conductivities (3-4 joules/m²/m-hour-°C) than glass, high hardness values (8 to 9), low thermal expansion (10-5/°K), variable dielectric properties that can be manipulated by composition and semi-conductor coatings, and good resistance to thermal shock. Bulk strength increases as the average crystal size decreases. Compressive strengths of 10,000-12,000 Kg/cm² are achievable for average individual crystal sizes of 0.7 μm with flexure and tensile strengths of 500-1100 Kg/cm² being achievable. However, terrestrial rocks generally display a factor of 10 less strength in both compression and tension⁴⁴ presumably due to the wide range of grain sizes.

Casting of bulk lunar soil has been discussed in previous reports on Lunar Colonies.³ Some of the compositions utilized in the cast-basalt industry⁴³ are similar to those of lunar soils. Lunar highland soils are somewhat enriched in Al_2O_3 and require somewhat higher melting temperatures than terrestrial basalts. Nevertheless, initial details are available for specific processing techniques that may be used with lunar soils. Because the properties of the products are dependent on the careful control of the growth of very fine-grained crystals, the shape and size of the product will determine the specific processing conditions. Thus the volume of seed crystals and times and temperatures of annealing must be determined for each specific product.

Two production techniques are employed. (a) Crystallization is initiated at a high temperature during molding and the thermal treatment after

molding completes the crystallization. This applies primarily to basaltic and diabasic compositions. (b) Shaping or molding is done in the glassy state. Crystallization is initiated at a lower temperature than in (a) and proceeds through a higher temperature where the crystallization is terminated by abrupt cooling. Either technique requires precise control over the cooling rate of the materials following pouring into the molds.

Volatile Components

The major species of volatiles released during heating of lunar soils are CO, CO₂, N₂, H₂, H₂O, SO₂, H₂S, CH₄ and a few other hydrocarbons.^{1,9,20} Minor amounts of He, Ar, Ne, Kr and Xe are also released, but total well under 100 ppm. Some O₂ is evolved at temperatures of 1300° to 1400°C. Most of the SO₂ is released above 1000°C. The thermal release patterns of gases from lunar soils have been well studied, and indicate several stages of gas-release that depend on the location of the volatile components in the soil.²⁰ Those components derived from the solar wind are located on the surfaces of grains, and are easily released at low temperatures. Those that are tightly bonded as part of a mineral structure, such as sulphur, oxygen and some carbon, are released only at high temperatures. The H₂O of lunar soil has its source in both terrestrial contamination and solar wind-implantation of protons that interact with oxygen which may originate from either the solar wind or minerals containing oxygen.

The weight loss of volatiles up to 1000°C is normally about 1000 ppm.²⁰ This loss generally increases to between 0.5 and 1.5% by 1400°C, much of

the increase resulting from the high temperature release of S and O, which may react with each other to form SO₂, or with other components to form CO₂, H₂O, and H₂S.

Oxygen will be produced in large quantities as a product of metals processing. It is not clearly apparent, however, that the retrievable small quantities of other individual species of gas would warrant the energy or volume and mass of equipment required for processing. In that many of these gases are utilized in cyclic processes it may be more economical to transport the gases in condensed form from earth. If any gases other than oxygen are to be retrieved from the lunar soils, the processing must be optimized for the specific species that are desired. Equilibrium among gases varies considerably with temperature, and the design of a processing system must take this into account. There is little doubt that existing technology is adequate to separate these species, but without a clearer justification for the need of large quantities that cannot be transported more economically from earth, detailed designs were not undertaken.

Location of Processing Plant

A transportation system with mass driver capabilities favors processing of raw material in space rather than on the moon. This conclusion is based on considerations of both developmental and operational costs, with the assumption of large demand for refined metals and oxygen in space. The results of a more detailed study can be briefly summarized.

The main motivation for processing material on

| ITEM | MASS (tons) | POWER INPUT (KW) | VOLUME (M ³) | HEAT OUTPUT (KW) | ^a TEMPERATURE OF HEAT (°K) | RADIATOR MASS (tons) |
|---------------------------------|----------------|------------------|--------------------------|------------------|---------------------------------------|----------------------|
| Iron reduction system: | | | | | | |
| solids processing | 171 | 66 | 100 | 66 | 300 | 0.8 |
| furnace/cooler | 25 | 18,700 | 50 | 18,700 | R | 4.5 |
| cent. furnaces/cooler | 23 | 6,620 | 20 | 6,620 | R | 1.6 |
| Carbothermic red. syst: | | | | | | |
| solids processing | 29 | 17 | 25 | 17 | 300 | 0.2 |
| furnace/cooler | 224 | 150,000 | 300 | 5,100 | R | 1.2 |
| Mg reduction furnace | 15 | 17,400 | 30 | 300 | R | 0.1 |
| Metal separation system: | | | | | | |
| distillation furnace | 74 | 73,700 | 300 | 0 | | |
| condenser | 30 | 10 | 100 | 73,700 | R | 17.6 |
| Carbon recovery syst: | | | | | | |
| catalytic reactor | 290 | 10 | 300 | 29,000 | 600 | 21.9 |
| condenser/electrolysis | 310 | 188,000 | 300 | 11,000 | 390 | 46.6 |
| decomposition bed | 13 | 10 | 20 | 31,000 | R | 7.4 |
| Misc. and utilities: | 181 | 361 | | 361 | 300 | 4.4 |
| Power plant: | 1,820(454,894) | | | | | |
| TOTAL | 3,205 | 454,894 | | 175,864 | | 106.3 |
| Total with radiators | 3,311 | | | | | |

Table 3. Estimates of Masses, Volumes and Power Requirements of the Processing Plant

^aR = radiator limited--800°K assumed

the moon before shipment is a saving of less than 50% in shipped mass. Costs of transportation and processing, however, are both dominated by their energy requirements, which are more than five times greater for processing than for transportation. Energy costs on the lunar surface are roughly eight times greater than in free space, due to higher transportation costs and the absence of continuous illumination. This motivates placement of the processing facility in free space, even at the expense of somewhat expanded mass driver capability; cost was lowered by a factor of two.

Further benefits are found in development. Lunar surface gravity is impossible to simulate on earth. Terrestrial gravity is easy to simulate in space, but difficult to simulate on the lunar surface, permitting free-space adaptation of terrestrial equipment with minimal space testing. With Shuttle availability, LEO testing of zero-gravity equipment should be simpler than corresponding tests on the lunar surface.

Mass, Volume, and Power Requirements

An estimate of the masses, volumes, and power requirements associated with the processing plant has been made, with system breakdown to the major component level. Table 3 describes a plant accepting 10 kg/s of raw material, or some 300,000 tons per year. The nature of the components allows parallel units in large plants and, therefore, suggests virtually linear scaling of plant mass with input from 1 kg/s on up.

The basis for power plant and radiation masses is straightforward (4 tons/MW and 10 kg/m²). For the remainder, masses were estimated from terrestrial equipment (standard ball mills, industrial electrolysis cells, etc.). Because no effort was made to allow for possible mass reduction for space use, masses are likely to be overestimates. A measure of performance for the system is that it produces its own weight in silicon, structural metals, and oxygen in less than six days.

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