3. Lunar Materials

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The mass requirements for O'Neill's Model 1 are half a million metric tons of soil to be launched from the Moon and about ten thousand metric tons of materials and people to be launched from Earth. Five thousand four hundred metric tons from the Earth would be hydrogen to combine with the lunar oxygen to make water at L5. The complete breakdown is illustrated in Table 5.

One of the first questions to be asked is whether we can get that hydrogen from the Moon. Unfortunately, however, there's no spot on Earth as anhydrous as the lunar surface.

No lunar water has been reported; only sample contamination by terrestrial water. There are not even minerals present which required water for their formation, and these minerals date over a four-billion-year period. The Moon is the most unlikely source that one could imagine for extracting hydrogen or water. Dust is the principal characteristic of the lunar surface. The dust is easy to work with. It contains material from virtually everywhere on the Moon. Particles less than one millimeter in size compose from eighty percent to, in some cases, ninety eight percent of the visible surface and the bulk of the regolith down to depths of many meters.

Figure 10 shows histograms of the mass distribution of various lunar soils from the Apollo 17 site. The horizontal scales are millimeters, microns, and the logrithmic ϕ-units used in sedimentology. These diagrams clearly show that the soil is extremely fine-grained, with average sizes which peak around sixty microns. There is a significant percentage of mass of soil in these samples less than four microns in size. There are soils returned from the Moon that are even finer-grained, with the order of ten percent of the material less than ten microns in size. This particle size distribution is the key to providing the hydrogen for the first space manufacturing facility, because this soil contain hydrogen implanted from the solar wind.

This unique property of the surface geology of the Moon is illustrated by the old poem:

Big fleas have little fleas
Which upon their backs do bite'em
But little fleas have smaller fleas
And so ad infinitum.

This is really what the lunar surface is like. Figure 11 shows a tip of a grain that's one hundred microns across. it is an agglutinate composed of grains that are stuck to one another by a glass matrix. The smallest grains that you can see in this picture are less than a micron in size. They go on down to tenths of a micron and smaller.

In that one-hundred-micron volume is a microcosm of the entire Moon, a somewhat representative sample of material from every place on the Moon that has been exposed to the solar wind. Each grain in this picture, down to the smallest size, has gas of solar origin distributed through it in two ways: in volume-correlated form - that is, distributed on a per-unit-mass basis through

Table 5 Model I Mass Requirements; Transportation; Salaries (Non-recurring Terrestrial Expenses)

	Mass and Costs of Transportation to L5 from:				
	Earth			*Moon*	
Item	Mass (KMT)(1)	Cost ($ × 10^9)(2)	Item	Mass (KMT)	Cost ($ × 10^9)(4)
Generator Plants	1.	.94	Aluminum	20.	0.4
Initial Structures	1.	94.	Glass	10.	0.2
Specially Fabricated Equipment	1.	.94	Soil, Rock & Construction Materials	420.	8.48
Machines & Tools	0.8	75	Oxygen for Water	44.8	0.91
2000 People & Equipment	0.2	.44(3)			
Dehydrated Food	0.6	.56			
*Liquid Hydrogen	5.6	5.24			
Totals	10.0KMT	9.81 × 10^9		494.8KMT	10 × 10^9
	*If one can obtain hydrogen from the Moon then				
	−5.6	−5.24	Lunar Hydrogen	+5.6	0.11
New Totals	4.4KMT	4.57 × 10^9		≃ 500KMT	10.11 × 10^9
New Transportation Total					15 × 10^{9}(5)

(1) Thousand Metric Tons
(2) $935/kg
(3) $4,410/kg
(4) $10 × 10^9 for lunar base to supply ≃ 500MT to L5 (or 4) for average cost of $20/kg.
(5) Revised project total (O'Neill 1974) would be approximately $25 × 10^{+9} with major expenditure being 8.4 × 10^{+9} for L5 and terrestrial salaries

each grain; and in surface-correlated form – evenly distributed on the surface of the grain. It's this last point that is important. Surface correlation is, I think, the key to obtaining hydrogen and other elements from the Moon for the early lunar operations, where a minimum of complexity is desired on the Moon and in space.

Figure 12 is a plot of concentration of an arbitrary species; e.g., in number of atoms per unit mass or per unit volume on the vertical (ordinate) scale; the horizontal (abscissa) scale is the radius of the grain size. For spherical grains, the surface area of the material goes up in inverse proportion to the average radius of the grains. For example, if a one-centimeter-diameter spherical grain were crushed into tenth-micron particles, its surface area would increase by a factor of 10^5.

Hydrogen, helium, the inert gases, and many

Figure 10 Particle Size Distributions of Various Lunar Soil Samples

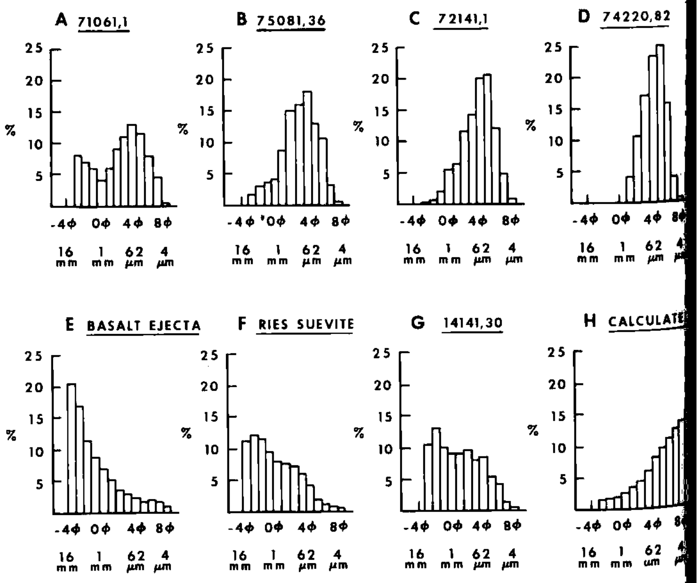

Figure 11 Micron Grain of Lunar Soil (1000 Magnification), Showing Agglutinate Composition

reactive materials such as carbon and nitrogen are distributed in surface-correlated form in the lunar soil. Hydrogen is the least surface-correlated of those examples. Sufficient surface correlation exists in many of the Apollo samples such that the bulk of the implanted material is actually contained in the grains under ten microns, which are a small fraction of the total volume of the soil. It appears possible to extract those grains either mechanically (sieving), electrostatically, or possibly by magnetic separation. The agglutinates are quite often separated from lunar samples simply by pulling them out with a bar magnet.

Figure 12 Species Contribution vs Particle Grain Size

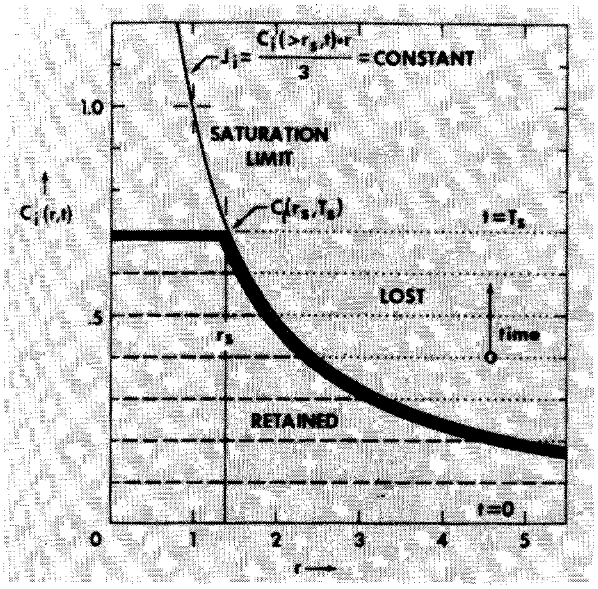

Figure 13 Photomicrograph of Lunar Material Showing 2%-5% Iron

The problem we face is a massive one, however: five thousand four hundred metric tons of hydrogen consists of 3 x 10^{33} hydrogen atoms. The typical bulk concentration of hydrogen in the lunar soil is the order of 2 x 10^{19} hydrogen atoms per gram, ranging in the Apollo 17 soil (not the best example) up to 9 x 10^{19}. The half-million tons of soil necessary for the construction of Model 1 would produce 4.5 x 10^{31} hydrogen atoms, or one and a half percent of what is needed. Further, we need in some way to sieve the smallest grains out of a volume which is sixty-six times larger to separate out the hydrogen-rich or volatile-rich component.

The half million tons of soil corresponds to a ditch five meters deep and 0.1 kilometer in radius. To obtain the necessary 5400 tons of hydrogen, we'd need to process material from a ditch 0.4 kilometer in radius and, again, five meters deep.

This seems like an enormous amount, but actually it is very much like digging in face-powder: if you undercut it, it collapses under the tool. As long as you don't hit large rocks, which you can navigate around, you can expend very little energy and still process this material. The mechanical energy required simply to lift the material up to a separating machine and then redeposit the residue would only require 1.8 horsepower operating continuously over the six year period. Even allowing a factor of ten or a hundred for the power actually required to extract the finest grains, this is not a particularly unwieldy number.

The task can probably be made much easier by careful selection of site, locating the very finest-grain material, going to special mineralogies, higher agglutinate contents, and high ilmenite contents, which are also iron-rich. It should be possible to get a rough idea of the location of these optimal low-latitude sites by orbital inspection on the basis of the Apollo data in hand. A polar orbiter will be required to survey the entire Moon, and in-situ testing will be required to determine the actual ideal sites.

Figure 13 indicates some of the possibilities raised by considering other special characteristics of the lunar material. This photo is about two or three hundred microns across, and shows crystal grains from vugs, inside grains of the lunar surface. They are pure iron blebs, of sub-micron size, distributed across the surface. Most free iron is associated with agglutinates. If you go to the very finest fraction of the lunar material, the quantity of pure iron can sometimes approach two to five percent by volume. It can be separated by straightforward magnetic separation techniques. It is also possible that surface-correlated carbon and nitrogen can be produced in quantities somewhat lower than that of the hydrogen for the same sample, possibly a factor of five. Again though, you can optimize this by careful selection of where you do your sieving.