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Lunar Beneficiation

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With the exception of igneous differentiation and possible fumarolic activity (volcanic exhalations), the Moon lacks all the major ore-forming processes that operate on Earth—aqueous concentration of crustal minerals, surface weathering of rocks, advanced fractionation of igneous rocks, and plate tectonic recycling of the crust. For that reason, natural concentrations of industrially valuable minerals (ore bodies) are far less likely to be found on the Moon than on the Earth (see James Carter's paper, earlier in this volume). But that is all the more reason for devising beneficiation processes to concentrate and extract the useful mineral components in lunar rocks and soils. Another important consideration is that nearly complete reagent recycling will be required for most of the processes proposed for producing oxygen, metals, and ceramics on the Moon. Reagent recovery will be greatly simplified by using simple input ore minerals. Examples of such minerals are ilmenite, the most abundant lunar oxide and a source of oxygen, iron, and titanium; anorthite, the chief source of lunar aluminum; and metallic iron/nickel fragments that occur in lunar soil. In addition, there may be significant amounts of chromite, sulfides, and phosphates in terranes that are rich in chromium and KREEP (potassium, rare earth elements, and phosphorus).

As an example of a useful mineral that can be beneficiated, McKay and Williams (1979) have estimated ilmenite abundance by microscopic count to be 15 and 20 percent by volume in Apollo 11 and 17 basalts and 2 and 5 percent by volume in Apollo 11 and 17 soils. Reduction of lunar ilmenite with hydrogen imported from Earth appears to be one of the more practical schemes for obtaining lunar oxygen. While the reported concentrations are significant, a more highly concentrated ilmenite extract would improve the efficiency of the reduction process.

Electrostatic Concentration

In 1985, I reported designing mineral electrostatic separators based on commercial models. With my separators, I demonstrated the electrostatic concentration of lunar ilmenite in the 90- to 150-micrometer grain size fraction of Apollo 11 soil 10084,853 to levels above 60 percent at collection points near the high-voltage electrode after one pass through a slide-type electrostatic separator in a nitrogen environment (figs. 1 and 2). Ilmenite behaved like a semiconductor and was separable electrostatically because the other major soil components, including the metal-bearing agglutinates, behaved like nonconductors.

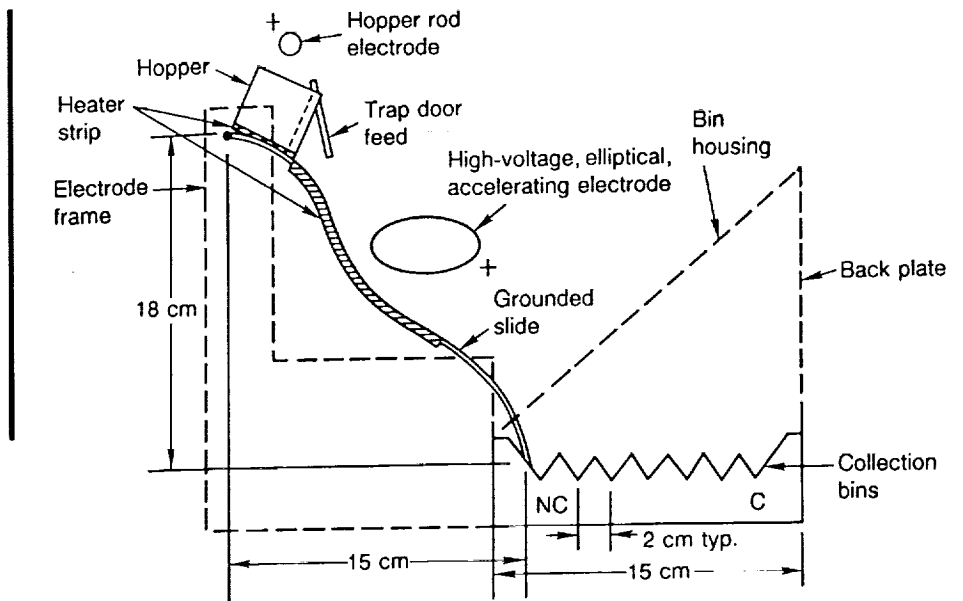


Figure 1

Mineral Electrostatic Separator, Slide Configuration

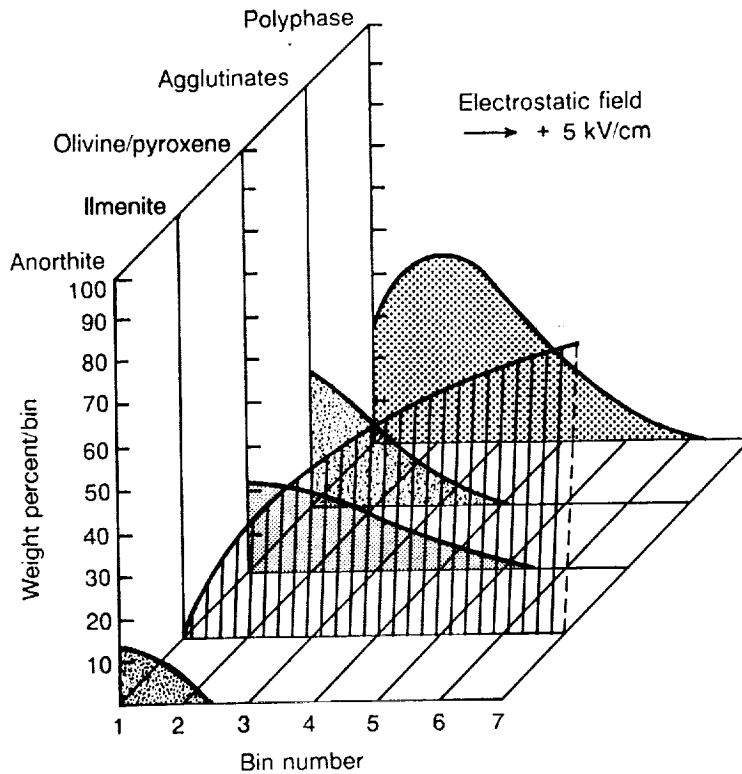


Figure 2

Electrostatic Separation in Nitrogen of Apollo 11 Soil 10084,853, 90-150 μm Fraction

Agglutinates are the major component of lunar soil, making up, on the average, 50 percent of the regolith. Most of the agglutinates contain finely dispersed metallic iron, which gives them a broad magnetic range that overlaps the magnetic susceptibility of other soil components, including ilmenite. For that reason, it is difficult to separate agglutinates from ilmenite

by magnetic means. However, the nonconducting behavior of the agglutinates allows them to be separated from ilmenite electrostatically. During separation, the soil sample was heated to approximately 150°C to drive off terrestrial water and enhance the contrast in conductivity between ilmenite and other mineral components (see fig. 3).

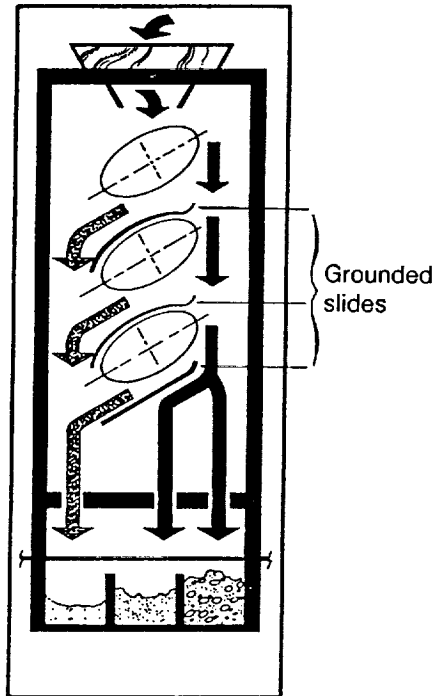


Figure 3

A Commercial Electrostatic Separator on the Lunar Surface

The mirror in this concept of an electrostatic separator on the Moon focuses solar radiation on the soil to be separated. Heating to about 100°C will increase the conductivity of the semiconductor ilmenite while leaving the conductivity of insulators like agglutinates unchanged. The enhanced contrast in conductivity increases the separability of these components of the lunar soil.

In the schematic, the arrows indicate the path of the soil feed and how it separates. The ellipses are cross sections of the high-voltage electrodes. The nonconducting materials fall to the far right. The middlings fall in the middle. The conducting and semiconducting materials fall to the far left.

In my electrostatic studies the lunar anorthite seemed to collect preferentially close to the grounded electrode (the feed hopper), but the slide design of the separator was not configured to take advantage of that.

The slide did enhance the density segregation of ilmenite by air (nitrogen) resistance. Ilmenite is almost twice as dense as the

other major soil components. Accordingly, electrostatic separation of the ilmenite in a vacuum, where air resistance was not a factor, was not as successful, and the mineral reached a maximum concentration of only 30 percent in one pass under those conditions (fig. 4). This, however, amounts to a fourfold increase compared to the starting concentration of 7 percent.

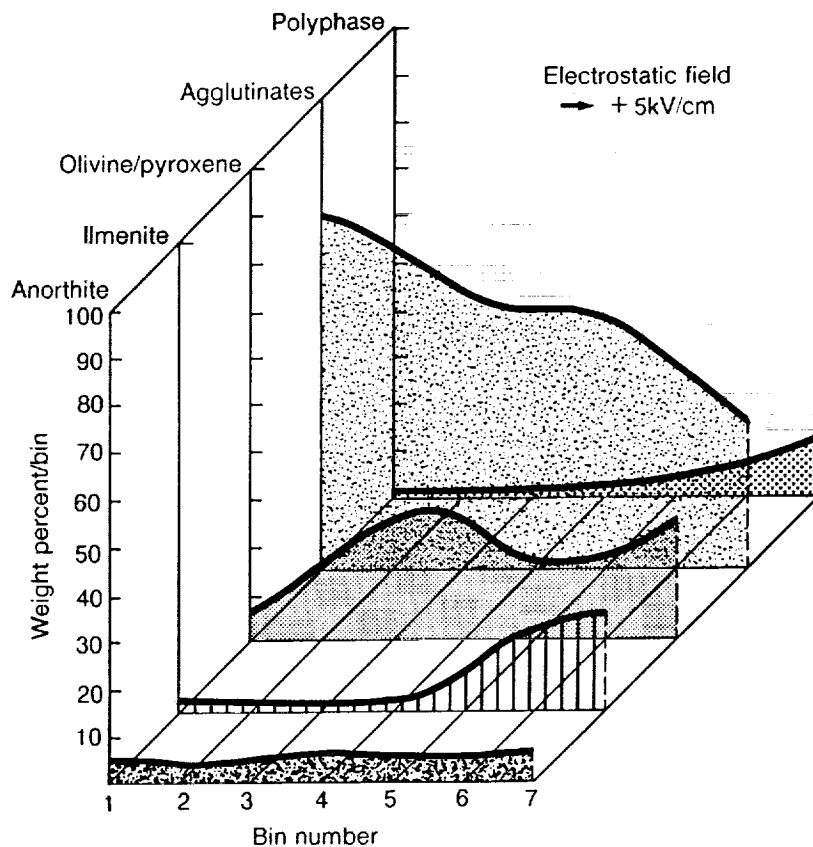


Figure 4

Electrostatic Separation in a Vacuum of Apollo 11 Soil 10084,853, 90-150 μ m Fraction

To improve yield in the vacuum of the lunar environment would require redesign of the electrostatic separation apparatus. A vertical, free-fall design (as seen in fig. 3) might be the best approach for separating lunar soil minerals according to their electrical behavior and would be especially appropriate in the lunar environment, where fall times are about twice what they are on Earth.

Magnetic Concentration

Unlike Earth soils, all lunar soils contain naturally occurring, particulate iron/nickel metal (FeNi), which is believed to derive from meteorite impacts. Lunar soil metal is likely to be an accessible and useful resource. Goldstein and his associates (1972, 1973) reported soil metal contents of 0.15 percent by weight in the size range 74 μm to 1.0 mm of three Apollo 16 soils and 0.05 percent by weight in a comparable size range of two Apollo 14 soils. If these occurrences are typical of the lunar highlands and maria, respectively, then there are at least 7 billion metric tons of accessible FeNi metal in the top 10 cm of soil over the entire lunar surface. And there may be substantially higher concentrations of surface metal in regions where iron meteorites have struck the Moon.

In 1981, I proposed a magnetic beneficiation method for concentrating lunar soil metal, using off-the-shelf permanent magnet separators and autogenous grinders. Projected yield was 552 metric tons per year of 99-percent pure FeNi powder. The specific energy required to extract the FeNi metal magnetically was 0.4 kWh/kg, an order of magnitude less than that required to smelt iron from typical ores. A major advantage of the concentrated metal powder product is that it may be formable directly by flexible, low-power powder metallurgical techniques to make a variety of tools, machine parts, plates, struts, wires, electrical contacts, and magnets. Near-theoretical density for these parts may be achievable by powder pressing in the high lunar vacuum. Furthermore, the product can be toughened to steel specifications by adding the right proportions of lunar oxides or titanium to the metal powder before pressing.

An all-magnetic method for beneficiating soil FeNi may present problems because of the large volume of iron-bearing agglutinates that have ferromagnetic properties. But Goldstein did achieve concentration of soil metal grains in the laboratory, using a very low magnetic field gradient on the Frantz Isodynamic Magnetic

Separator, and a comparable technique might be adaptable to industrial operations on the Moon.

I suggest that metal particles first be separated from ilmenite and other soil components magnetically and then, because the ferromagnetic agglutinates may have separated with the metal particles, electrostatic separation could be used to eliminate the agglutinates from the desired metal fraction. Comparable combinations of techniques may be appropriate for extracting other soil components, like anorthite, chromite, and phosphates.

Lunar Soil Sizing

What volatiles are known to exist on the Moon tend to be concentrated in the fine soil fractions. For example, Gibson et al. (1987) showed that hydrogen implanted by the solar wind increases tenfold as particle size decreases—from 12 ppm in the 90- to 150-micrometer fraction to 127 ppm in the less-than-20-micrometer fraction of five representative regolith samples. Overall hydrogen content is about 40 ppm. At 75-percent recovery from the top meter of soil over the entire lunar surface, that is enough hydrogen to make a water lake 10 meters deep and 44 kilometers in diameter. The helium content of the soil is about the same as the hydrogen content. Furthermore, 0.04 percent of the lunar helium is the isotope ^3He , which is much

rarer on Earth and which is a potentially important fusion energy fuel (Wittenberg, Santarius, and Kulcinski 1986). Helium-3 may be the only lunar product that can be returned to the Earth at a substantial profit. Accordingly, lunar soil sizing techniques will be vital to extracting rare and precious lunar volatiles. In addition, sized soil input is required to optimize mineral yield by electrostatic and magnetic separation methods.

Dry sizing techniques that may be appropriate to the lunar environment include electrical sizing, screening, and gas elutriation.

Electrical Sizing

In 1984, I measured the trend of increasing charge-to-mass ratio with decreasing grain size in terrestrial analogs of common lunar regolith minerals and subsequently demonstrated electrostatic sizing of terrestrial ilmenite over the particle size range of 500 down to 90 micrometers (figs. 5 and 6). The previous year, Peter Castle, at the University of Ontario, demonstrated an electrical sizing of conducting spheres in a comparable size range. In both cases, air turbulence limited the smallest separable size to 90 micrometers. Accordingly, electrical sizing in a vacuum is indicated for grading of fines smaller than 90 micrometers.

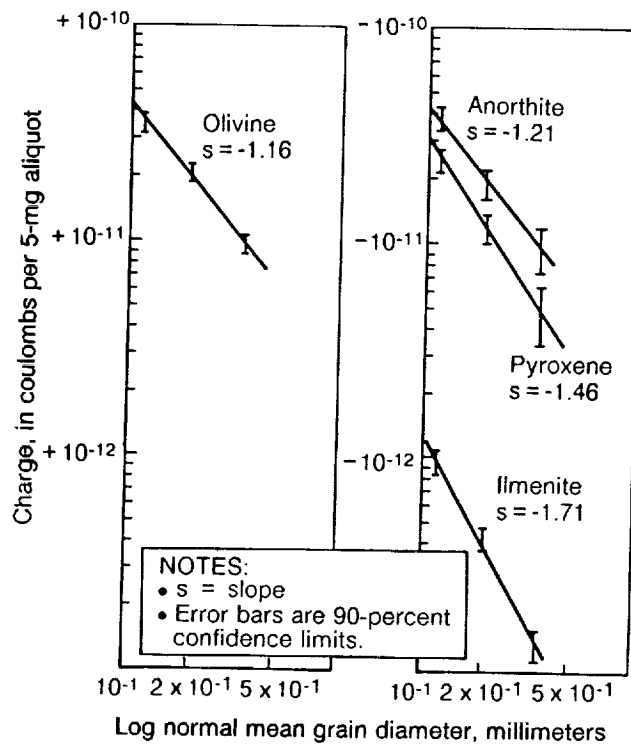


Figure 5

Contact Charge Acquired on Aluminum by Terrestrial Olivine, Anorthite, Pyroxene, and Ilmenite as a Function of Grain Size

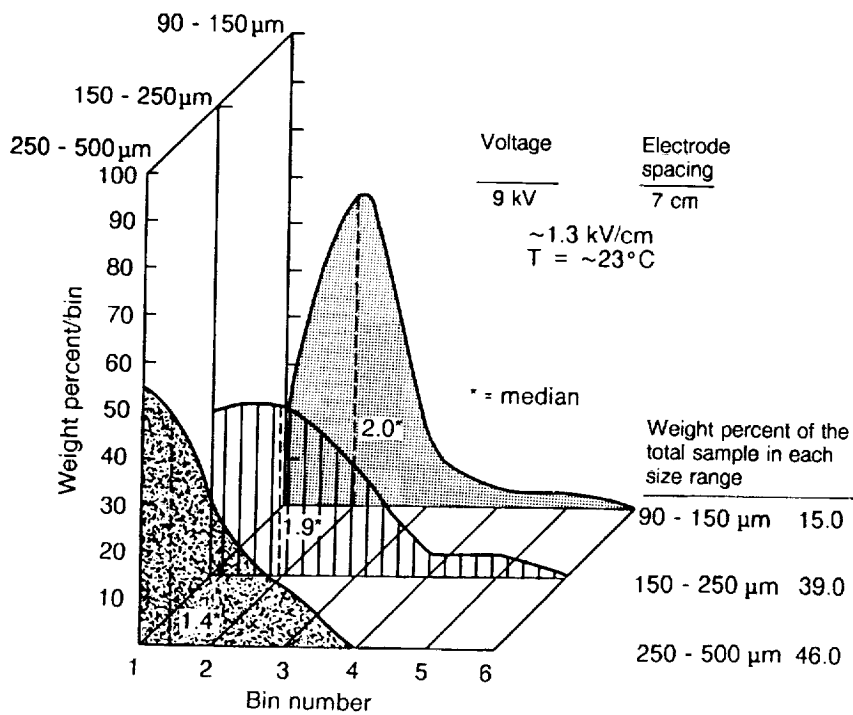


Figure 6

Electrostatic Sizing of Comminuted Ilmenite

Screening

Sieves are available for screening particles ranging from 5 to 30 micrometers at 5-micrometer intervals. It is unlikely, however, that such fine sieving can be accomplished without suspension of the fines in a gas or fluid medium. Even under those conditions, fines sieving is a laborious process. The fluid most likely to be available on the Moon is oxygen, and, since cryogenic temperatures can be relatively easily maintained there, it might be instructive to attempt lunar soil sieving in liquid oxygen. This may be a practical technique because it is unlikely that significant oxidation of lunar soil components will occur at liquid oxygen temperatures (below -183°C). In addition, the only combustible component is FeNi metal, which is less than 1 percent of the soil by weight and which is predominantly encapsulated in glassy agglutinates.

Gas Elutriation and Classification

Gaseous classifiers, cyclones, and fluidized-bed separators operate by stratifying particles in a rapidly moving gas stream according to size and density. They are available on the market for sizing fine particles from 0.5 to 35 micrometers. These devices can deliver the narrowest size

ranges (at best, at the small end, a spread of about $0.2\ \mu\text{m}$) on a commercial scale (kilograms to tons per hour). On the Moon, gas classification might be done in oxygen. The possibility and consequences of oxidizing reduced lunar soil phases under these conditions will have to be considered and experimentally determined. However, it appears unlikely that, by commercial standards, significant oxidation of soil components will occur in dry gaseous oxygen at sufficiently low temperatures (e.g., -20°C) over the short period required for gaseous classification (minutes).

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