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LUNAR RESOURCES -- TOWARD LIVING OFF THE LUNAR LAND

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Space is now an accessible part of the human environment, and it behooves us to learn in the broadest sense what's out there, how it got there, and how it works. In the narrower context of modes of exploration that place men and women in space, we should also learn how to keep ourselves healthy and safe, how to carry out activities in space, and how to use what we find there. Whatever the reasons may be for our activities in space, we should learn through those activities what the practical importance of space may be.

Why the Moon?

We can particularly improve our assessment of the value of space for human activities through the experience of living on the surface of another planetary body and learning how to use its indigenous materials. The nearest body appropriate for this is the Moon, which has properties and resources suitable for such exploration. The Moon, like low-Earth orbit, geostationary orbit, and lunar orbit, is part of near-Earth space, part of the Earth-orbit environment. Because it is close, in the near term it is the easiest and safest body outside of Earth to use. We know more about it than we know about any other planet except Earth. A Moonbase will build on the experience of the Apollo missions. Even with these advantages of proximity and our knowledge of its surface, the Moon still offers substantial technological challenge in engineering, mining, manufacturing, construction, and life support.

Economics will ultimately dictate where and what kinds of material we will use in space but, if we take a conservative approach, we might conclude that for near-term use in near-Earth space there are only two choices. One is the Earth and the other is the Moon. Because the Moon is the most likely object for testing and developing the first technologies for sustaining human presence on another planet, it is also the most likely economical near-term supplier of extraterrestrial material for use in near-Earth space. In the longer run, we may find it economical to use far more distant bodies such as near-Earth asteroids or Phobos to supply materials to near-Earth space (e.g., Lewis and Lewis, 1987). As we do not know what specific materials any of these bodies has to offer or what the physical states of their surfaces are, we cannot readily design technologies to use on them; we therefore assume that their use is decades in the future.

The Earth as a source for materials to use in space has the advantage of well developed technologies and manufacturing capabilities. It has the disadvantage of relatively high gravity and a consequent, unavoidable penalty in energy for lifting materials from its surface into orbit. The Moon has the advantage of intermediate gravity, low enough to enhance the payload/liftoff-energy ratio relative to lifting from Earth, but high enough to be of practical use in separating products from residues. Transport of lunar material to low-Earth orbit is particularly attractive if aerobraking supplants rocket energy for achieving that orbit. Whatever the actual cost of using a lunar materials may be, provided they do not require extensive crew time to produce, the largest part of that cost is for hauling the lunar factory from Earth to the Moon (e.g., Simon, 1985). Forseeable technologies that would reduce the cost of transporting materials from Earth, even to low-Earth orbit, would almost equally reduce the cost of operations on the lunar surface.

Technologically, the Moon is underdeveloped. Earth technologies cannot readily be transplanted to the lunar surface because conditions and starting materials there are not those found or used on Earth. The Moon also remains largely underexplored. It is underexplored physically, so that we have no satisfactory assessment of the range of materials it has to offer. It is underexplored conceptually, in that we have not devoted enough effort or funds to learn how we might make use of what we already know is there. Many uses and technologies have been proposed, but few have been tested and none has been fully developed. The lead time for research and development is ten to fifteen years for the simplest proposed technologies, and we need serious laboratory work on them now if we are to test them, let alone hope to use them, at the proposed lunar outpost.

Lunar Resources and Surface Conditions

So, what is abundant on the Moon, and how might we use it? Here, we take a conservative view and accept as resources only those materials we know from Apollo experience to be common and present in such large quantities that we would not require further *on-surface* exploration to verify their existence as ore bodies. Abundant materials in the lunar highlands are breccias (rocks that consist of fragments of earlier rocks, produced on the Moon by the impacts of the meteoroids that made the heavily cratered lunar surface) and "soils" (the unconsolidated, pulverized products of the cratering impacts). In the lunar maria, prevalent materials are basaltic lavas and soils, and there may be substantial deposits of pyroclastic glasses (lunar volcanic ash). (The lavas and pyroclastic deposits would require on-surface verification as ore bodies because: thicknesses and continuity of lavas with specific characteristics, e.g., high proportions of ilmenite, would need to be demonstrated and thicknesses of pyroclastic deposits would need to be determined.)

In addition to these material resources, the lunar surface offers intermediate gravity, high vacuum, and dependable sunlight (half the time). It also offers extreme temperatures (120 °C in the sun, -170 °C in the shade), no atmosphere to transfer heat or scatter light, clinging dust, and two-week-long days and nights.

The most likely material for initial use is lunar soil. The principal chemical constituents of the soils (e.g., Haskin and Warren, 1990) are oxygen (about 45% by wt.), silicon (about 21%), aluminum (about 13% in highland soils, 5% in mare soils), calcium (in most soils 8 - 10%), iron (some 15% in mare soils, 6% in highland soils), and magnesium (about 5%), plus some sodium and, in some mare soils, significant titanium (up to about 6%). Of course, all of the chemical elements are present in the soils, but most are present in minor or trace concentrations. There may be ores for some of the minor or trace elements; certainly, extensive amounts of chemical separation took place, as indicated by small, specialized fragments in the lunar sample collections. However, because the Moon lacks internal water, ores of most types we find on Earth are unlikely to be found there.

Guidelines for Early Lunar Technologies

Overall, simple transplantation of terrestrial technologies to the lunar surface seems inappropriate. Materials that are common on the lunar surface would be uncompetitive as starting materials for most terrestrial extraction processes. We especially would disdain them as sources of air and water, which we regard as free and abundant on Earth. Lunar surface conditions would also be unsuitable for most terrestrial technologies. Because of this, we tend to regard them (and conditions on the surfaces of other objects in the solar system) as impediments. However, with new ideas and proper understanding, we should be able to turn at least some of these conditions into advantages.

Initially, all operations on the lunar surface (as elsewhere in space) will be awkward and expensive. Thus, the simplest technologies that can produce crucial products will presumably be the first technologies developed (e.g., Haskin, 1985). We can speculate that characteristics of desirable initial lunar technologies would include the following: Such technologies would have few and simple steps, including minimal preparation of feedstock and minimal effort to recycle reagents. They would require minimal material (reagents plus factory) to be brought from Earth. They would make efficient use of energy, or at least of power other than direct sunlight. They would be easy to install, have few moving parts, and be easy to maintain and operate, and thus require little astronaut time. They should be robust with respect to physical jarring during transport and installation. They should be robust with respect to feedstock composition: the ore body should be easy to mine and batches of feedstock should not require extensive compositional monitoring.

However unusual lunar soils may seem when compared with terrestrial ores, they are an excellent resource in terms of their chemical compositions and, for some purposes, their physical characteristics. It is convenient to illustrate this in the sort of everyday terms one might use if one were a pioneer settler on the Moon. Our pioneer settler must have the perspective of a chemist, however, to recognize much of the potential of the soil as a resource.

The Lunar Water Works: As pioneers, our first concern might be food and water, especially since the Moon has the reputation of being very dry and barren of carbon. It is proposed that there may (e.g., Arnold, 1979) or may not (e.g., Lanzerotti and Brown, 1981) be water at the lunar poles, but we ignore that possibility in our conservative scenario. Instead of water, let us consider the abundance of its chemical components, oxygen and hydrogen. The lunar supply of oxygen is enormous: oxygen is the most abundant chemical element (by weight, some 45%) in the lunar soils and rocks. It is chemically combined in those materials and must be extracted, as discussed below.

In contrast, concentrations of hydrogen are very low, but the total quantity available is nevertheless great. Lavas erupted from the Moon's interior contain such low amounts of hydrogen (and carbon and nitrogen) that we have been unable to observe them even with modern sensitive instruments, in contrast to terrestrial lavas, which typically contain at least 0.5% water. The lunar surface, however, has been bathed for billions of years in the solar wind, a flux of ionized atoms from the exterior of the sun. These ions embed themselves in the surfaces of the grains of soil that lie on the Moon's surface. The lunar surface is repeatedly "gardened" by infalling meteorites, so old, solar-wind-rich grains are buried and fresh grains exposed. In this way, large amounts of hydrogen have become buried in the soil, enough to produce (if combined with lunar oxygen) about one million U. S. gallons (about 3.3 million liters) of water per square mile (2.6 km^2) of soil to a depth of two yards (1.3 m) (Haskin, 1990). This hydrogen can be extracted by heating the soil to about 700 °C. Supplying the Lunar Water Works is a matter of technology and economics, but not a matter of availability of hydrogen and oxygen on the Moon.

The Lunar Farm: Like hydrogen, carbon and nitrogen are abundant in the lunar soil. Like hydrogen, they are derived from the solar wind and are present in very low concentrations. They are obtained along with hydrogen when lunar soil is heated. All the other nutrients necessary to life are likewise present in the soil. In principle, just as they do on Earth, plants should be able to extract these nutrients directly from the soil, once we have provided them with adequate lunar water, carbon dioxide, oxygen, and nitrogen. In practice, such soils would probably not be very fertile until their minerals had reacted with water, and hydroponic means of farming might be needed initially.

The Lunar Filling Station: At least initially, an important mode of transportation to and from the Moon base will be rockets. Hauling the fuel and oxidizer for these from Earth will be expensive. It may prove cheaper to provide them from lunar soil. The fuel of choice might be hydrogen. For perspective, consider the production of 40 tonnes of hydrogen per year, as reasonable estimate of the amount needed for all transportation from low-Earth orbit in the early Moonbase era. That amount can be obtained from just 0.3 square kilometer of soil mined to a depth of one meter (Haskin, 1990).

Alternatively, lunar transport vehicles might burn a metal such as iron, aluminum, or silicon, even though these are less efficient rocket fuels than hydrogen. All three are major constituents of lunar soils, from which they can be extracted from chemical combination with oxygen. Each is a byproduct of one or more proposed processes for extraction of oxygen.

We need an oxidizer for the fuel, and oxygen is very abundant, although it is not trivial to extract it from the soils. Several techniques have been proposed, including extraction of oxygen from ilmenite by using hydrogen gas (e.g., Gibson and Knudsen, 1985; Williams, 1985), extraction by using carbon monoxide gas (e.g., Rosenberg et al., 1965; Cutler and Krag, 1985), extraction by processing with hydrofluoric acid or fluorine (e.g., Waldron, 1985; Burt, 1990), and extraction by electrolysis, either with a flux (Keller et al., 1989) or without a flux (e.g., Haskin et al., 1990, discussed below).

The Lunar Lumber Yard: Suppose we decide we need a new structure on the Moon or in space; what will the Lunar Lumber Yard have to offer? A case can be made that the "boards" of space construction will be made of glass. Molten lunar soil can be cast into silicate beams, rods, and sheets, be extruded as tubes, and be spun into fibers. These may have greater strength than similar products on Earth because in the space environment there is no water to react with their polymer bonds.

Iron, aluminum, and silicon are byproducts of oxygen extraction from lunar soils. Iron and aluminum can be fabricated into beams and rods for structural support. They can be drawn into wires, both for structural use and for use as electrical and heat conductors. All three can be used as mirrors or mirror coatings to reflect sunlight.

The unprocessed soil itself can serve as thermal shielding to moderate habitats and other environments against the broad, diurnal temperature fluctuations at the lunar surface. It can also serve as radiation shielding against cosmic rays and solar flares. Partially distilled in a solar furnace, it seems possible that the residue from the soil might take on the composition of a good cement, and the water to turn it into concrete could be obtained from local sources, as mentioned above. Distilled further, the residue would be very refractory and could serve for heat shielding.

The Lunar Power Company: The Moon receives plentiful and predictable amounts of sunlight, and sunlight will surely be the eventual source of nearly all electrical power and heat used by the lunar pioneer. Except at very restricted locations at the lunar poles, sunlight is locally available only half the time, however, and for some purposes, the temporal distribution of sunlight is inconvenient. Storing energy derived from the sun over the two-week-long lunar night seems difficult, and might have to be done in the form of hydrogen, metals, and oxygen whose extraction was powered by solar energy. Thus, a strong case can be made that the power used initially on the Moon should be nuclear.

Initially, it may be economical to bring high yield solar panels to the Moon from Earth. Eventually, electrical power will probably be derived from lunar silicon, a byproduct of oxygen production, or from lunar ilmenite, recently shown to be photovoltaic. Conversion need not be efficient if a local material simply obtained is used as the photovoltaic.

Electrical power may be the first major import to the Earth from the Moon (once the souvenir market has been satisfied). Large arrays of relatively low-yield solar cells can be placed on the

Moon to supply large amounts of power for transmission to Earth (Criswell and Waldron, 1985). Also, lunar ^{3}He has been proposed for use as a fusion fuel superior to tritium (^{3}H) in that it is not radioactive, does not have to be made in nuclear fission reactors, and yields a proton instead of a more destructive neutron when it fuses with deuterium (^{2}H) (Wittenberg et al., 1987). The use of iron, aluminum, and silicon to coat mirrors to move sunlight around was indicated above.

"Magma Electrolysis," a Proposed Lunar Technology*

We are investigating electrolysis of molten silicate as a means of producing oxygen and metals for use on the Moon and in near-Earth space. (See also Oppenheim, 1968; Kesterke, 1971; Lindström and Haskin, 1979). Most of our effort so far has been to determine the nature and kinetics of the electrochemical reactions and the conductivities and other parameters necessary for design of a test cell. We have not yet designed a production-scale cell, but we have a rough idea of its characteristics (Haskin et al., 1990).

We envision a steady-state operation. The feedstock for the cell would be lunar soil that had been sieved to remove the small proportion of material larger than 0.3 cm. As the soil was fed into the cell, it would melt; the heat for melting would be furnished by "excess" electrical heat released into the melt owing to its resistance. The cell would have a volume of about one cubic meter and anode and cathode areas of about thirty meters each. Oxygen would be produced at the anode, and iron, silicon, or an alloy of the two would be produced at the cathode,

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*The term "magma electrolysis" is catchy (e.g., du Fresne and Schroeder (1983); because to geoscientists the term "magma" indicates naturally occurring melts, we generally use the term "molten silicate electrolysis."

depending on the composition of the silicate melt in the cell. The operating temperature of the cell would be between 1,200 and 1,400 °C.

We estimate that the power required to produce one tonne of oxygen gas per 24 hours would be about 0.54 Mw, of which some 0.11 Mw would be used to melt and heat the feedstock, 0.19 Mw would be used to separate the oxygen and metal from chemical combination, and 0.24 Mw would be "excess" resistance heat, some of which would be needed to make up for radiation losses from the hot cell, and the rest of which would be available for other uses. In addition to the one tonne of oxygen gas, the cell would produce (for an average melt composition) some 0.64 tonne of iron and 0.62 tonne of silicon. About 4.8 tonnes of soil would pass through the cell per 24 hours, so some 2.5 tonnes of spent silicate melt would have to be removed along with the oxygen and metal. All products of the cell would be useful; nothing would need to be discarded. Potential uses are discussed above.

This process would satisfy many of the criteria set forth above for early lunar technologies. The cell proper would have no moving parts,although the equipment to mine, sieve, and introduce the lunar soil would and that to remove and store the oxygen might. Producing the oxygen, metals, and spent silicate would be a one-step process; we have not considered how to handle the products, an activity common to all proposed processes. The mass and size of the cell would be modest compared to the equipment for most proposed alternate processes (e.g., Eagle Engineering, 1988).

The power requirements would also be competitive with those of proposed alternate processes, if we include in the comparison the ancillary steps required by those processes such as ore refinement and reagent recycling that would not be needed for silicate electrolysis. The cell would need continuous electrical power, however, so that its contents would not freeze during the lunar night; initially, this requirement may best be met by use of nuclear power.

The process would use common lunar soil; any common soil found by the Apollo or Luna missions would be acceptable, although prior knowledge of the general type of soil might enable optimization of cell design or startup protocols. Different feedstocks would require somewhat different initial conditions of temperature and electrical potential but, once the bulk composition of the melt had been established in the cell, probable variations in feedstock composition would not greatly affect cell temperature or operating potential.

The main identified and unsolved problems of the process center around finding suitable materials for the electrodes and container. Iron and silicon form alloys with most metals. Molten silicate is very corrosive. Anodes can probably be made of platinum or coated with it, and cathodes can probably be made of high-temperature iron-silicon alloys. The container may have to be made of spinel, which would be brought into equilibrium with the silicate melt.

Conclusions

Lunar soils contain in abundance the materials required for life support, construction, and transportation. The high cost in energy of lifting material from the Earth's surface suggests that, in the near term, lunar material should be considered for use both on the Moon and in low-Earth orbit. However, most conventional technologies are not suited to efficient processing of lunar material, so new technologies need to be developed. Additional ideas are needed, but most crucial is investment in thorough testing of existing ideas on a laboratory bench scale. Development of those that prove promising in the laboratory should be begun immediately, because of the long lead time to prepare robust units for testing or use on the Moon.

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