THE MOON AS A PRACTICAL SOURCE OF HYDROGEN AND OTHER VOLATILE ELEMENTS L. A. Haskin, Dept. of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130

Current folklore has it that the Moon is so poor in H, C, and N that these elements would need to be supplied from an external source for use at a Moon base. Organic geochemists who received Apollo samples for study shocked us with the news of how barren the Moon is of organic matter. We have come to view the Moon as a desert without life-enabling constituents. Contrary to our first impressions, however, these elements are abundant enough to supply Moon bases and to serve as components of fuels for use in low-Earth orbit or for extensive transportation to other points in space.

A typical cubic meter of lunar soil has a mass of about 1.6-2 tonnes and contains ~100g of H [e.g., 1,2,3], 200 g C [e.g, 3,4], and 100 g N [e.g., 3,4,5]. The upper two meters of the lunar regolith thus contain approximately $8x10^9$ tonnes of H, $1.5x10^{10}$ tonnes of C, and $8x10^9$ tonnes of N. These amounts do not rival those on Earth, but are nonetheless substantial. Converted to water, this amount of H would form a Lunar Great Lake some 70 km long, 10 km wide, and 100m deep. Thus, the problem is not so much one of low abundance as one of cultural shock that these particular elements are not available almost free of charge as they are to most of us on Earth. On the Moon, they have to be mined.

Quantities of H, C, and N in the upper two meters of the Moon are enormous in terms of life support. The surface density of C (assuming only the upper two meters) is ~200 g/m^2, more than one-third the surface density of ~540 g in living organisms on Earth (where the value for the oceans is greater than for the continents). The ratios of H (~6:1) and N (~0.5:1) to C in the lunar soil exceed the corresponding ratios (~2:1 and ~1:40) for the organic portions of living matter. The other volatile element of strong biological and technological interest, oxygen, must be released mainly by more severe methods but, being the most abundant element on the Moon, it is hardly in short supply.

Consider cheese as the propotypical lunar organic material; the quantity of H in a cubic meter of lunar soil equals that in 12 ounces (336 g) of that commodity. For a more balanced lunch, from a single cubic meter of lunar soil one could produce two cheese sandwiches, two sodas (sweetened with sugar), and two plums, with C and N left over.

Quantities of H, C, and N in the upper two meters of the lunar soil are also large in terms of use for fuel. The Shuttle external tank carries about 13 tonnes of H_2 per flight. At this rate of use, the quantity of H in the upper two meters of the lunar soil corresponds to some 600 million shuttle flights. To furnish the hydrogen for ten thousand such flights would require mining only 0.002% of the lunar surface.

The procedure for extracting H and other volatile elements is relatively simple. These elements can be smelted as compounds from lunar soil by heating to temperatures of 700 ^oC and higher [e.g., 1,2]. Accompanying their release will be that of noble gases, some sulfurous gases, and, depending on the soil, other relatively volatile elements. The mixture of gases can be reacted with lunar oxygen, then separated as H_2O, CO_2, N_2, SO_2, and noble gases.

Consider production of 40 tonnes of H per year, roughly the amount anticipated for use with an Orbit Transfer Vehicle to carry items from low-Earth orbit to geostationary orbit. This would require gathering and heating of some $8x10^5$ tonnes of soil per year. Suppose, arbitrarily, that processing is done only 120 days per year. The amount of soil to be handled per day would then be 6,700 tonnes, or ~3,800 m^3. The heat required to raise 6,700 tonnes of soil to 700 ^oC is about $1.3x10^{12}$ calories. If all that heat were used up in the process, this would be a heating rate of some 62 megawatts; however, heat from depleted soil can be used to warm incoming feedstock, so the actual sustained rate would need be only a few megawatts. Five megawatts of solar flux, for example, is the amount falling on an 175m square. It might be efficient to convert the heat to microwaves to spread it rapidly through the feedstock; lunar soil is a poor conductor of heat. At 700 ^oC, the combined pressure of H and the other gases, assuming a porosity of about 40%, would be some 14 atmospheres.

The question, then, is one of economics, not one of abundance. Is it easier or cheaper to obtain H, C, and N from the Moon, or to supply them from Earth? Given a base on the Moon, the less expensive source would seem to be the Moon. It is difficult to believe that it would be cheaper to obtain these elements from near-Earth asteroids or Phobos for use one the Moon or in Earth orbit. Simple heating of soil, while not trivial to do, is not complex as technologies go. Heating is presumably the technology that would be used on all planets that have volatile elements or compounds, including water, bound in their regoliths.

There is much interest in whether there may be water ice trapped in the regolith of permanently shaded floors of polar lunar craters. This consideration, while one of considerable scientific interest, is of doubtful economic interest. It should not be a major consideration in whether to have a Moon base or where a Moon base should be located. It may be more difficult to emplace and operate a base at the site of such water, or to transport water-laden regolith to a site nearer the lunar equator, than to extract the locally available hydrogen wherever the base is located.

References: 1. DesMarais et al. (1974) Proc. Lunar Sci. Conf. 5th, 1811. 2. Bustin et al. (1984) Lunar Planet. Sci. XV, 112. 3. For summary of H, C, N concentrations, see Haskin and Warren, Chapter 8 of Lunar Sourcebook (in press) 4. Chang et al. (1974) Lunar Sci. V, 106. 5. Muller (1973) Proc. Lunar Sci. Conf. 4th, 1625.