

WATER AND CHEESE FROM THE LUNAR DESERT: ABUNDANCES AND ACCESSIBILITY OF H, C, AND N ON THE MOON

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The Moon has been underrated as a source of H, N, C, and other elements essential to support life and to provide fuel for rockets. There is enough of these elements in each cubic meter of typical lunar soil to provide a substantial lunch for two, if converted to edible forms. The average amount of C per square meter of the lunar surface to a depth of 2 m is some 35% of the average amount per square meter tied up in living organisms on Earth. The water equivalent of H in the upper 2 m of the regolith averages at least 1.3 million liters per square kilometer. Mining of H from a small fraction of the regolith would provide all the rocket fuel needed for thousands of years. These elements can be removed from the soil by heating it to high temperature. Some favor the unproven resources of Phobos, Deimos, or near-Earth asteroids instead of the Moon as a source of extraterrestrial material for use in space, or Mars over the Moon as a site for habitation, partly on the basis that the chemical elements needed for life support and propellant are readily abundant on those bodies but not on the Moon. Well, the Moon is not as barren of H, C, and N as is commonly perceived. In fact, the elements needed for life support and for rocket fuel are plentiful there, although the ore grades are low. Furthermore, the proximity of the Moon and consequent lower cost of transportation and shorter trip and communication times favor that body as the logical site for early acquisition of resources and extraterrestrial living.

ABUNDANCES OF H, C, N, P, S, AND NOBLE GASES

By Earth's standards, the Moon is very dry; no free-standing water ice has been found on it and hydrous minerals are essentially absent from the acquired lunar samples. That does not mean that water is inaccessible there, however. There may be water of cometary or meteoritic origin trapped in the cold regolith of permanently shaded crater floors at the poles (Arnold, 1979; see also Lanzerotti and Brown, 1981, for arguments against), but we ignore that possible source in this analysis. We consider not how much water is present, but how abundant the elemental constituents of water are. One constituent, O, is the most abundant element on the Moon; some 44% of the mass of lunar surface rocks and soils is O. The other constituent, H, is so scarce in the lunar interior that we cannot claim to have measured any indigenous H in samples of mare basalts. Nevertheless, thanks to implantation of ions from the solar wind into the grains of lunar soil, there is enough H in a typical cubic meter of the lunar regolith to yield more than a pint and a half of water (≈ 0.71). Despite consideration of this resource by others (e.g., McKay and Williams, 1979; Bustin et al., 1984; Carter, 1984; Gibson et al., 1988), the availability of H seems not to be generally recognized.

The concentration of H in typical lunar soil is $\approx 50 \mu\text{g/g}$ (e.g., DesMarais et al., 1974, mean for 18 soils $59 \pm 16 \mu\text{g/g}$; Bustin et al., 1984, mean for 15 soils $50 \pm 23 \mu\text{g/g}$), for a total of $\approx 100 \text{ g/m}^3$ (the density of lunar soil is $\approx 1.75 \text{ g cm}^3$). Based on the soils sampled in the deep drill strings of the Apollos 15, 16, and 17 missions, these concentrations hold to a depth of 2 m and probably more. At $50 \mu\text{g/g}$ of H, this corresponds to >1.5 million liters of H_2O per square kilometer to a depth of 2 m or one

million gallons per square mile to a depth of 2 yd. There are some $3.8 \times 10^{13} \text{ m}^3$ of regolith per meter of depth at the lunar surface and, thus, some 7.6×10^9 tonnes of H in the outer 2 m of the Moon. To put this into perspective, this corresponds to about 6.8×10^{10} tonnes of water, or the amount in a lake of dimensions 10 km wide \times 68 km long \times 100 m deep. Since we do not know the average depth of regolith with this concentration, and since some soils may contain as much as $100 \mu\text{g/g}$ H, this is a conservative estimate. The problem is not that H is scarce on the Moon, but whether it is economically accessible.

Along with this $\approx 100 \text{ g per m}^3$ of H are $\approx 100 \text{ g}$ of N, $\approx 200 \text{ g}$ of C, $\approx 1.8 \text{ kg}$ of S, $\approx 1 \text{ kg}$ of P, and noble gases ($\approx 20 \text{ g}$ of He, $\approx 2 \text{ g}$ of Ne, $\approx 2 \text{ g}$ of Ar, $\approx 1 \text{ g}$ of Kr, and $\approx 1 \text{ g}$ of Xe) (Haskin and Warren, 1991). The upper 2 m of the lunar regolith thus contains $\approx 7.6 \times 10^9$ tonnes of N, $\approx 1.5 \times 10^{10}$ tonnes of C, $\approx 3.6 \times 10^{11}$ tonnes of S, and $\approx 2 \times 10^{11}$ tonnes of P, along with the $\approx 7.6 \times 10^9$ tonnes of H (Fig. 1).

In terms of life support, these amounts are enormous. Each cubic meter of typical lunar soil contains the chemical equivalent of lunch for two—two large cheese sandwiches, two 12-oz sodas (sweetened with sugar), and two plums, with substantial N and C left over. The quantity of N in a 75-kg human corresponds to the amount present in only 36 m^3 of soil, or an area of $6 \text{ m} \times 6 \text{ m}$ mined to 1 m depth. The $\approx 200 \text{ g}$ C per square meter of lunar surface compares favorably to the estimate of 540 g of C per square meter of the Earth's surface in living organisms (Borchert, 1951). Thus, the total mass of lunar C corresponds to the average amount of terrestrial C in living organisms in an area of Earth as large as 1.4 times that of the United States. Collection of even a small fraction of the Moon's budget of H, C, N, P, S, and other elements essential to life into a suitable environment on the Moon would support a substantial biosphere.

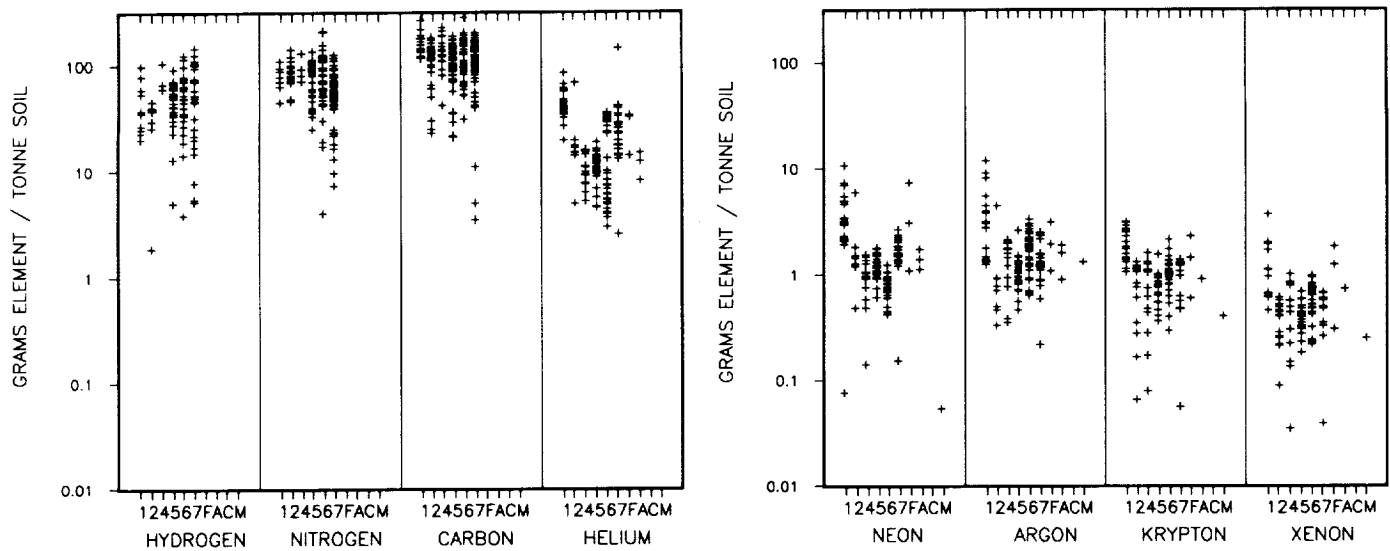


Fig. 1. Concentrations of H, C, N, and noble gases are shown for individual lunar soils from various lunar sites. Included with the data for soils are data for several regolith breccias, which have many characteristics in common with soils. Units are grams of element per tonne of soil (or μg element per g soil). The Apollo landing sites are denoted by the numbers 1, 2, 4, 5, 6, and 7 for the Apollos 11 through 17 missions. The Luna sites are F, A, and C (for Fecunditatis, Apollonius, and Crisium). The Antarctic meteorites, which represent one or more unknown highland sites, are denoted M. The database and format for the figure are based on *Haskin and Warren (1991)*.

The current economically appealing use foreseen for these resources is for propellant. In particular, lunar H as a fuel for spacecraft would enhance the value of lunar O as an oxidizer, because then neither H nor O would have to be hauled to low Earth orbit (LEO) from Earth. An annual rate of use of ≈ 300 tonnes/year for lunar O has been estimated for movement of satellites from LEO to geostationary orbit (GEO) toward the end of this century. The corresponding (unfavorably high) stoichiometric amount of H is only 40 tonnes/year. Even at a rate of use a hundred times that, the supply of H would last nearly two million years.

For further perspective, the external tank on the space shuttle contains about 100 tons of liquid H_2 at liftoff. The radius of the crater (without rays) Copernicus is of the order of 100 km. The amount of H beneath an area of regolith equivalent to the area of Copernicus is some 1.6 million tonnes, or enough for 17,000 shuttle tankloads. The greatest amount of H that could be used for propellant during the next several decades would not leave strip mine scars visible to the naked eye on Earth.

There simply is no shortage of H, C, N, or O at the lunar surface. These elements occur in a manner unlike that to which we are accustomed on Earth. All except O can be readily extracted into the gas phase in high yield by heating of lunar soil, and some O is extracted along with the H. On heating of soils, most H is evolved as H_2O or H_2 by the time a temperature of $700^\circ\text{--}800^\circ\text{C}$ is reached (e.g., *Gibson and Moore, 1972*), although some H is not removed until the melting temperature of $1050^\circ\text{--}1100^\circ\text{C}$ is approached or reached (e.g., *DesMarais et al., 1972*). Substantial fractions of C are also removed by heating to $700^\circ\text{--}800^\circ\text{C}$, but temperatures as high as $950^\circ\text{--}1000^\circ\text{C}$ are required to remove substantial fractions of the N, and temperatures $\geq 1200^\circ\text{C}$ appear to be required to remove C and N quantitatively (e.g., *Simoneit et al., 1973*; *Chang et al., 1972*; *DesMarais et al., 1972*). Thus,

the problem of accessibility of H, C, and N reduces to one of the economics of heating substantial quantities of lunar soil, capturing the evolved gases, and separating the different gaseous components from each other.

A ROUGH ESTIMATE OF PARAMETERS FOR EXTRACTION OF HYDROGEN

Hydrogen may be extracted from lunar material by innovative processes not based on simple heating of lunar material (e.g., biological extraction; *White and Hirsch, 1984*). Hydrogen and the other solar-wind-implanted, relatively volatile elements may conceivably become available in great quantities as by-products of some other venture, e.g., the mining of ^3He . It has been suggested that lunar ^3He could be mined in large quantities to provide fuel for fusion reactors that would supply the bulk of Earth's power for many decades (*Wittenberg et al., 1987*). That isotope, which could possibly replace radioactive ^3He in the most commonly considered type of controlled fusion, is more dilute relative to ^4He on the Earth than in the lunar soil. A substantial portion of the lunar surface might be mined to obtain ^3He , and H, C, N, and other noble gases would be extracted along with it. If this were to take place, we would be faced with capturing and conserving an embarrassingly high amount of H, C, and N. From here on, we ignore that possibility and consider the production of H for use on the Moon or in LEO, mainly as rocket fuel for transport of spacecraft between LEO and GEO. Given below are estimated parameters for producing 40 tonnes of H per year and the assumptions underlying those parameters.

At ≈ 100 g H per m^3 (>50 g H per tonne) of lunar soil (density about 1.75 to 2 g/cm^3), roughly 8×10^5 tonnes of soil must be processed per year. Assume that solar heating will be used, and

that processing is done only 120 (24-hour) days per year. Then, 3800 m^3 (6700 tonnes) of soil must be processed per day.

Assume that the bulk of the H will be released by 700°C . We estimate the heat capacity of lunar soil to be $\approx 0.3 \text{ cal}/^\circ\text{C}/\text{g}$ [the measured values of *Hemingway et al.* (1973) go only as high as 300 K]. The heat required to warm one day's worth of soil to 700°C is thus $\approx 1.4 \times 10^{12}$ calories. This amounts to some 63 MW of power, a very substantial amount. However, most of the heat can be recovered following the extraction step and used to preheat the incoming feedstock. Thus, only a few megawatts of power will actually be required if the power can be delivered efficiently.

This heat can be obtained from the sun. During the 120 days of greatest light, the solar energy flux averages roughly $10^{-3} \text{ MW}/\text{m}^2$. If we can transfer solar energy to the extraction chamber and use it with 80% efficiency, then we need about 12 MW of solar flux. This corresponds to the energy falling on an area of $\approx 1000 \text{ m}^2$, or a 32-m square. It may be a challenge to collect and focus this energy, but the energy is certainly there. It may be more practical to convert the energy from direct heat to some other form (e.g., microwaves; *Meek et al.*, 1984; *Tucker et al.*, 1984) to concentrate it into the relatively small volume of the processing chamber, especially since the soil is an excellent insulator. In that case, the efficiency would be lower, and a larger area of collection would be necessary.

The conductivity of lunar soil has been measured *in vacuo* (*Hemingway et al.*, 1973), but not under pressure of gas, and moving gas is an effective heat transfer agent. In fact, the gas pressure will be substantial and will (or through appropriate engineering design could be made to) affect the rate of heat transfer. Some 70 mols of gas per cubic meter of soil will be produced. Soil porosity is normally $\approx 40\%$, since the bulk density is $\approx 1.75 \text{ g}/\text{cm}^3$ but the particle density approaches $3 \text{ g}/\text{cm}^3$. At 700°C , the ≈ 70 mols of gas produced per cubic meter of soil would produce a pressure within the pore space of ≈ 14 atm. This might be sufficient pressure to drive a turbine to stir the soil to increase the rate of heat transfer, or to pump the gas, etc. The reversible isothermal expansion of 70 mols of gas per cubic meter of lunar soil from 14 atm to 1 atm corresponds to a power rate of 65 kW for the $3800 \text{ m}^3/\text{day}$ of soil processed. Taking mechanical advantage of the pressure affects reactor design.

If the gas is removed from the system at low pressure, the anticipated low permeability of the soil on the incoming side might be expected to prevent the gas from leaking out of the entry port in a continuous feed system. (The mean particle size of lunar soils is quite small, e.g., $\approx 40\text{--}80 \text{ }\mu\text{m}$ for mature soils from Apollo 17; *McKay et al.*, 1974.) If the gas were allowed to build up to its full pressure (≈ 14 atm), however, the back pressure would equal that of a column of soil some 470 m tall.

The required flux rate of soil through the chamber also depends on the efficiency of heat transfer. If we assume that in the extraction chamber the soil can be heated to the necessary $700^\circ\text{--}800^\circ\text{C}$ in one minute, and we assume a cross section for the chamber of 10 cm height by 2 m width, the length of the chamber has to be 13 m to accommodate the throughput of 3800 m^3 of soil per day. The velocity of the soil would have to be 0.78 km/hr ($22 \text{ cm}/\text{sec}$), and the residence time of the soil in the chamber would be about 1 min. These calculations are meant to illustrate that sizes and rates are within the range of feasibility, and should not be taken as an attempt to design a reactor.

At the time of mining or some time prior to gas extraction, the soil would need to be sieved to remove particles of large

enough diameter to interfere with any moving parts of the reactor, for example, the minor portion consisting of particles of diameter $>5 \text{ mm}$. (Since material of diameter $>5 \text{ mm}$ is relatively rare in the regolith, the gravel thus collected could be a valuable by-product of the process.) The solar wind is implanted mainly at the surfaces of soil grains, so concentrations of solar-wind-implanted elements are somewhat surface correlated. Thus, sieving the soil to obtain a fine size fraction would thus produce a richer feedstock. *Carter* (1984) has discussed in detail the possible advantages of sieving the soil and subjecting only the finest fraction to the extraction process. He demonstrates that two-thirds of the H is present in the $<20\text{-mm}$ portion of most soils. Whether it is better to highgrade the soil or simply to remove only those particles large enough to damage the reactor becomes one of economics; sieving to such a fine size would add significantly to the difficulty of handling the soil, but would reduce the amount of soil that had to be heated.

The volume of soil to be processed per day, 3800 m^3 , must be handled twice, on input and after extraction. If the soil is mined to a depth of 1 m, the area of excavation per day would be $62 \text{ m} \times 62 \text{ m}$, roughly comparable to that of a football field, a modest amount by terrestrial mining standards and only about 2% of that required to provide the ^3He needed to support a 500-MW fusion power plant (e.g., *Li and Wittenberg*, 1991). In a year's time, the total amount of soil moved (120 days' worth, moved twice) would be $9 \times 10^5 \text{ m}^3$. This corresponds to excavation and replacement of the soil to 1-m depth within a radius of 380 m of the extraction plant over a year's time. This would be a substantial, but not a formidable, challenge to early lunar technology.

The gaseous products of the heating would include H_2O , H_2S , CO , CO_2 , NH_3 , HCN , and noble gases (e.g., *Simoneit et al.*, 1973). The easiest means of separating the components from each other may begin with combustion to produce H_2O , CO_2 , N_2 , SO_2 , and noble gases, then use differential freezing or adsorption to separate the combustion products from each other. For this, perhaps advantage can be taken of the low temperature (-170°C) of shaded regions on the Moon and of the adsorptive capacities of lunar soils. *Fuller et al.* (1971) and *Cadenbead et al.* (1972) give parameters for lunar soils for adsorption and desorption of gases.

CONCLUSIONS

The Moon should not be overlooked as a source for H, C, or N for use in space, for either life support or rocket fuel. Available quantities of all three elements are substantial. These elements are released as gaseous elements and compounds when lunar soils are heated to high temperatures. This method of extraction is quite unlike those used to obtain these materials on Earth, but the sun can serve as the principal source of energy for the processes. The likely method of extraction of water from martian soil (the regolith tested by the Viking mission contains 0.1–1 wt% H_2O) is heating, but only to $350^\circ\text{--}500^\circ\text{C}$. (*Biemann et al.*, 1976). Pyrolysis to $500^\circ\text{--}600^\circ\text{C}$ is also the probable method of extracting these materials from near-Earth asteroids, based on the assumption that some of them will prove to be similar in character to Carbonaceous meteorites (e.g., *Simoneit et al.*, 1973). The trade-off is one of ease of access (and, for the present, certain knowledge of the nature of the lunar regolith) and higher extraction temperatures vs. far more distant, poorly characterized sources and somewhat lower temperatures.

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