EXTRACTING SOLAR-WIND VOLATILES REQUIRES PNEUMATIC SIZE SEPARATION AND TRANSPORT.

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Summary: Pneumatic separation of the finest fraction of lunar soil, and transporting only the material with the highest concentration of volatiles, enhances the (already significant) economic viability of pneumatic conveying in partial gravity. A rough estimate exists for the solar-wind gas content of the "average" regolith [1]; however, we are still working to understand how the amount of each solar-wind gas varies geographically.

Background: Solar wind gases are a source of hydrogen, helium, carbon, nitrogen, and other volatiles that will be valuable commodities on the Moon (e.g. [2]), and these gases can be released at modest temperatures (Figure 2 [3]). Experimental data [4] exist to show that finer grain size soil has increasing hydrogen content (Fig 1), and other solar-wind gases show a similar trend, because the gases are surface-correlated [5].

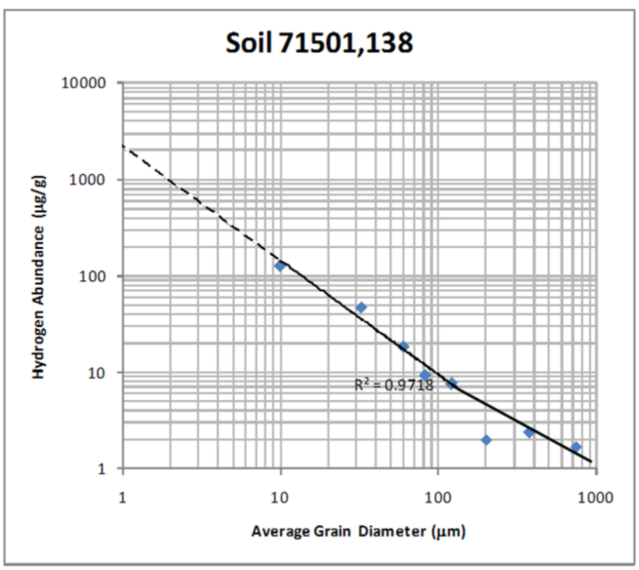

Figure 1. Weight percent of adsorbed hydrogen in lunar soil increases exponentially as grain size decreases.

Concentration of solar-wind gases at finer sizes results from the solar wind volatiles being implanted to depths of a few hundred to a thousand nanometers. At finer grain sizes, these thin surface layers makes up a higher and higher proportion of the bulk material so that the concentration of solar wind volatiles per gram increases significantly.

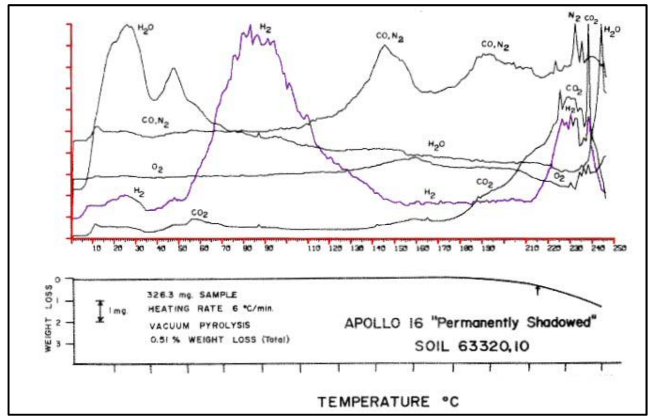

Figure 2. Thermal gas release data for Apollo 16 sample 63320. Note hydrogen release peak at 500°C (from [3]).

While the data of [4] only go down to 10 micrometers mean grain size, extrapolation of this well-behaved correlation curve to 1 micrometer size shows a potential concentration of more than 2000 µg/g, a factor of about 60 increase compared to the bulk soil. A concentration of 2000 µg/g hydrogen is the equivalent of 1.6 % water. This is similar to the amount of water that has been proposed for many sites in the permanently shadowed polar regions.

Figure 3. Pneumatic particle size separation down to 1.7 micrometers has been achieved in the laboratory.

The most mature soils generally have a larger amount of adsorbed solar-wind volatiles (because of their longer exposure time), and ilmenite-rich soils also tend to be enriched in solar-wind hydrogen [6, 7]. Moreover, there is some evidence that soils from shadowed areas (and areas buried under a few cm of regolith) may contain more volatiles than do regolith samples from fully sunlit areas [8].

Pneumatic Separation Benefits: Separation of regolith according to size strongly enhances the efficiency of many proposed ISRU processes [9-13]. Here, we expand upon the approach of [14, 15] to beneficiate lunar soil while simultaneously recovering solar wind gases.

We have developed a method to pneumatically separate particles of 1.7 micrometers size and smaller from lunar soil [16]. This method, coupled with the pneumatic separation and transportation techniques developed by [14], offers the capability to separate and process particles of very small size, with the expectation of enhanced yield as described above.

Figure 4. Honeybee's pneumatic transfer system proof of concept, in a vacuum chamber.

Pneumatic separation and transport gives us the potential to obtain the vast majority of the Moon's resources in a simple and economical way, anywhere on the Moon. For oxygen production (as well as other volatiles), the richest part of the regolith (the dust) can be separated *in-situ* from the bulk soil. Only a small fraction of the regolith will be transported, because the majority of the solar wind gases are contained within the smallest fraction.

Conclusion: We are still working to understand how the amount of each solar-wind gas varies geographically. In addition to the overall increase of some volatiles in specific areas, there is evidence that some areas are depleted in one volatile and enriched in another [17]. As we continue to improve our prospecting methods for solar-wind volatiles, we are also developing the technology for extracting these consumables. The next step is a trade study to quantify the savings gained in mass and power for this system, in comparison to other proposed methods.

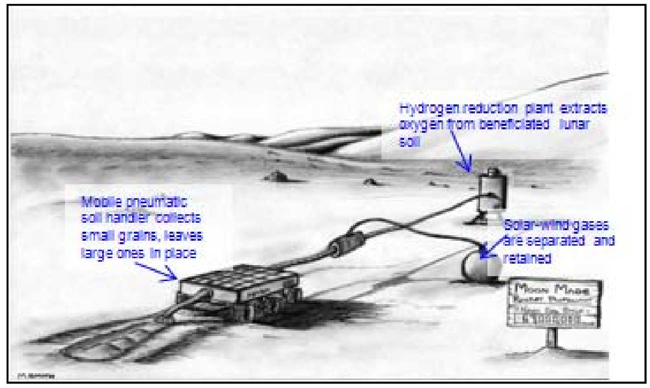

Figure 5. Concept of a mobile pneumatic regolith collection and transport system.

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