The Feasibility of Helium-3 as the Low Hanging Fruit of Lunar Commercial Mining

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Introduction: Helium-3 (3He) is a rare commodity which is in demand from a variety of industries and users who pay high prices for it, \$2000/liter, \$1M per ounce, \$35M/kg.

3He is an extremely rare isotope on Earth, but relatively abundant on the Moon. Nearly all the He on Earth is the isotope Helium-4 (4He).

Current market demand for 3He is recently estimated at \$192 Million per year[1]. US demand before 2010 was ~100,000 L/yr, but it is now rationed to ~15,000 L/yr. Studies to date of lunar extraction have relied on overly optimistic projections for demand for nuclear fusion which does not exist and will not for the foreseeable future. We propose a new considerably scaled down version of lunar miner with production of 1 kg per year. Such a system could be realistically built and financed to support the established market.

At Space Initiatives Inc (SII), we have been monitoring the 3He market for several years, and we have reviewed the work of University of Wisconsin Fusion Technology Institute (FTI). We believe their design approach is overkill for the existing market. We will design a smaller system for minimum weight to minimize launch costs. Our system will be sized to service the EXISTING market, as opposed to the hypothetical future market predictions of the FTI.

We believe that 3He is the "low hanging fruit" of lunar ISRU and commercial lunar mining, since the commodity can be sold directly into an existing robust market. Other lunar resources, such as Hydrogen, Water and Oxygen, require a substantial investment in lunar and cislunar infrastructure, such as propellant storage depots, handling and distribution systems. For 3He, on the other hand, no new infrastructure is required, beyond the initial mining equipment. The scale of mining equipment needed for 3He extraction is considerably smaller than for mining other lunar commodities, and the up-front capital investment needed will be correspondingly much smaller.

At present, Astrobotic CLPS/Viper prices of \$199.5M for 450 kg for lunar soft landing, a gear ratio of 3 gives 150 kg payload return to Earth. The value of 150 kg of 3He is \$4.5 Billion, which would exceed the transport cost by a factor of 22.6x.

Terrestrial Supplies: The current supply of 3He is only produced from the radioactive decay of tritium in the artificial environments. In order to maintain the integrity of the tritium critical to the operation of nuclear warheads, the 3He is removed by the National Nuclear Security Administration (NNSA) at the Savannah River Site in South Carolina[1]. The byproduct of decay, 3He, has been publicly auctioned by the Department of Energy's National Isotope Development Center (NIDC)[2]. Some 3He was available from Russia, but that availability varies, and has not been enough to fully offset the reduction in US domestic supplies. Economic sanctions now make it impractical to obtain He3 from Russia.

It is theoretically possible that 3He can be recovered from natural gas [3] or from ocean floor magma vents [1], however the concentration (parts 3He per part 4He) is much lower than on the Moon, 0.2 ppm to 30 ppm versus 1/3100 on the Moon. The energy cost of extracting He from natural gas currently exceeds the market price of the He produced and separating 3He from the extracted He would add further to the cost.

The Market: Current market demand for 3He is recently estimated at \$192 Million per year. The upside potential is unknown since demand currently far exceeds supply. It is entirely possible that the market could expand by an order of magnitude if unlimited supplies were available.

3He is in great demand by for aerospace inertial systems, hospital MRI systems, neutron detectors, fusion research. The market for neutron detectors has been expanding, the biggest consumer is the oil and gas industry, who use them for exploration and well logging. Another major user is the Department of Homeland Security, who use neutron detectors at all ports of entry to the USA to scan for illegal importation of fissile materials.

Methods of 3He Extraction and Separation:

Agitation: There is a significant amount of volatile release by agitating or moving the undisturbed regolith fines. Losses of 3He from Apollo 11 fines due to agitation may be at least 40% of the concentrationin of undisturbed regolith, which was determined through the empirical knowledge of the solar wind volatile concentrations from the Apollo lunar regolith samples and mass spectros copy data [4]. Since no recent literature after the conclusions of Schmitt validate this method. If Schmitt is correct, then the size and mass of our miner could be drastically reduced. However, the amount of size reduction would need to be confirmed through experimentation.

Electrostatic Separation: After agitation, it is important to separate the fine regolith dust from the volatiles otherwise the dust may cause significant damage and depletion to the compressor and fluidized chamber pump over time. The dust is collected on electrode plates and then be shaken off into a hopper and transferred to the heater.

Heating: Not all the 3He can be released by agitation, heating the regolith further extracts the 3He along with the other volatiles. It is proposed that the regolith ideally be heated to about 700℃ to release over 80% of the 3He from the regolith [5].

The University of Wisconsin's Fusion Technology Institute's (FTI) lunar miner designs employ a heat exchanger which alone consumed 12.3 MW of power. This is because the amount of 3He extracted was a rate of 33 kilograms per year with concentration of 3He at 10 ppb, a rate of 157.3 kilograms per second and 85% of the heat being retained [6]. The SII system is targeted to extract 1 kg of 3He per year.

Molecular Separation: After the bulk gas has been removed from the regolith, the molecular separation process begins. In order to obtain pure 3He, all other gases must be removed. This is done in two phases. The first phase is to separate out the non-He gases, such as H, N, and CO_2. This is typically done through adsorption, through the use of chemical getters [7]. Getters chemically react with one or more of the non-He gases, removing it from the bulk gas.

Isotopic Separation of *3He and 4He*: The key differences lie in the nuclei of the atoms. 4He possesses two protons and two neutrons, while 3He also has two protons but only one neutron. One of the starkest differences between 3He and 4He is its superfluid phase. A superfluid is a liquid with zero viscosity. 4He undergoes its superfluid transition at 2.17 K while 3He does not transform into a superfluid until 0.03 K [7].

Entropy Filter: The entropy filter is a proposed design of a system that is effectively able to separate 3He and 4He by utilizing the quantum effects occurring in superfluid He [8].

Membrane Filtration: This method uses a nanoporous graphene membrane to filter 3He through the membrane by taking advantage osf slight deviations in the tunnelling probabilities of the two isotopes of 3He and 4He [9]. However, these calculations are largely theoretical. Furthermore, a cost effective method of producing a graphene membrane of equally distributed pores of the same size has yet to be discovered.

Other Forms of Isotope Separation: Methods such as "heat flush" and "super-leak" use the same cryogenic principles and He superfluid properties as the entropy filter method. Cryogenic distillation has been modeled theoretically, but there is a lack of practical physical designs that have been researched.

Thermal diffusion: This method is unique from other methods by taking advantage of the difference in thermal diffusion coefficients of He isotopes rather than cryogenic and superfluidity properties [10]. However, little work has been done in the research or application of this process since the 1950s.

Conclusion: It appears that heating is the best method for releasing the gases trapped within the regolith. Extraction via agitation also appears to be a promising method. However, there is a severe lack of experimentation regarding both of these techniques. Determining if these methods are viable is critical to analyzing the feasibility of 3He extraction on the moon.

There are several methods to separate He isotopes, most of which require He to be cooled to extremely low temperatures.

Technical Objectives: SII propose to obtain the minimum cost-effective lunar processing system (Minimum Viable Product or MVP). This has never been done with a view to real world markets and economics.

We have identified the three main steps of extracting 3He – mining, extraction, and separation – and the U Michigan team will be performing experiments on more efficient methods of extracting 3He from a simulant regolith via heating and agitation processes not covered in literature. U Michigan will then test how to collect and store the volatiles released and eventually how to separate pure 3He.

Finally we will attempt to establish a reference design to determine the capital cost and amortization time.

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