Lunar Helium-3: Mining Concepts, Extraction Research, and Potential ISRU Synergies

Aaron D.S. Olson[1]
NASA Kennedy Space Center, FL, 32899, U.S.A

This paper describes various methods and designs specifically proposed for mining helium-3, and summarizes the methods, results and potential implications of recent research on helium extraction from lunar regolith simulant. This paper also touches on the potential synergy of lunar propellant production with helium-3 mining and some of the recent advancements in fusion technology related to future helium-3 fueled fusion reactors.

I. Introduction

Nuclear fusion could play an important role in meeting the demands of the Earth's energy future. Helium-3, a light isotope of helium with two protons and one neutron in its nucleus, could be fused to produce power based on the nuclear fusion reactions below:

$$D + {}^{3}He \rightarrow p\ (14.68\ MeV) + {}^{4}He\ (3.67\ MeV)$$

$${}^{3}He + {}^{3}He \rightarrow 2p + {}^{4}He \quad (12.86\ MeV)$$

Fusion power plants using these two reactions would produce far fewer high energy neutrons compared to nuclear fission reactors, leading to a drastic reduction in radioactivity and thus a massive reduction in the amount of residual radioactive waste [1]. The ^{3}He fusion fuel cycles are favorable compared to the deuterium-tritium (DT) nuclear fusion reaction in several ways. First, there is the possibility of higher energy conversion from fusion power to electricity due to the output power being carried through charged particles and not high energy neutrons that require a thermal cycle. Second, increased safety and ease of maintenance, relative to DT reactors, is possible with ^{3}He reactors due to the reduction of shielding required and the lack of induced radioactivity. Lastly, there is a reduced risk of proliferation with ^{3}He reactors which is also due to the reduction in neutron production. Helium-3 is not abundant on Earth [2]. There is only about 100 kg of presently available ^{3}He on Earth [3]. This amount would be sufficient for research and reactor development but would not significantly impact global energy production. Fused with deuterium, ^{3}He could produce ~19 MWyr/kg of fusion energy [4]. The available 100 kg could produce 1.9 GWyr of fusion energy. The limited amount of recoverable ^{3}He on Earth means that these future fusion reactors would have to be fueled by ^{3}He from somewhere else in the solar system.

Lunar samples brought back to Earth from the Apollo 11,12,14-17 missions and the Luna 16 and 20 missions showed that ^{3}He is present in the lunar regolith from over 4 billion years of bombardment from the solar wind. After reviewing Apollo soil sample analysis in 1985, researchers from the University of Wisconsin's Fusion Technology Institute (FTI) first proposed the use of lunar ^{3}He to generate clean and economical nuclear power [1]. FTI researchers estimated that there could be at least a million tonnes of ^{3}He within the first 3 meters of depth into the lunar surface. One million tonnes of ^{3}He, fused in a $D^{3}He$ reactor, could produce 19 million GWyr of electrical energy [4]. This is ~7 times the amount energy projected to be used for the entire 21st century [5].

---

[1] Physicist, NASA Kennedy Space Center Swamp Works Electrostatics & Surface Physics Lab, and AIAA Member.

In 2021, there are several commercial companies working to develop fusion reactors that could be fueled with ^{3}He. These companies have secured over a billion dollars to develop their technology and are planning to bring reactors to market as early as the 2030s [6].

II. Lunar Helium-3 Mining System Concepts

The Wisconsin Center for Space Automation and Robotics (WCSAR) was formed in 1987, as one of NASA's Centers for the Commercial Development of Space, to study how ^{3}He could be mined from the Moon. Researchers at WCSAR produced several mining concepts including mobile miners that excavate and process lunar regolith and in-situ volatile release and capture approaches.

A. Characteristics of Solar Wind Implanted Helium

Helium-3 nuclei make up approximately 0.002% of the solar wind [7]. Solar wind particles are emitted at 300-900 km/s (or 0.5 -4.0 keV/amu) with an average flux of 3 x 10^{10} ion/(cm^2-s) and an average speed of 450 km/s near the Earth [3], [8]. At an energy level of 1 keV/amu, ^{3}He particles are implanted into ilmenite about 26 nm deep and the other solar wind constituents are implanted between 14 and 32 nm deep [9]. Helium appears to be preferentially retained in titanium dioxide rich minerals, like Ilmenite, that are more abundant in the Lunar Mare regions [10]. Apollo 11 samples (from Neil Armstrong's bulk sample 10084) averaged 11.8 parts per billion (ppb) and ranged from 9.22 to 17.9 ppb in ^{3}He concentration [11]. Apollo samples also showed that helium concentration varies with particle size, as approximately 88% of the helium in Apollo 11 sample 10084 was found in particles smaller than 100 µm [12]. Helium concentration does not appear to be correlated with depth into the lunar surface [13].

Solar wind implanted gases, like helium, can be extracted from lunar soil by heating. Mass spectrometer analysis on Apollo 11 sample 10086, heated in a vacuum furnace, first illustrated the release rate behavior of the various evolved gases [14]. This behavior is shown in Fig. 1.

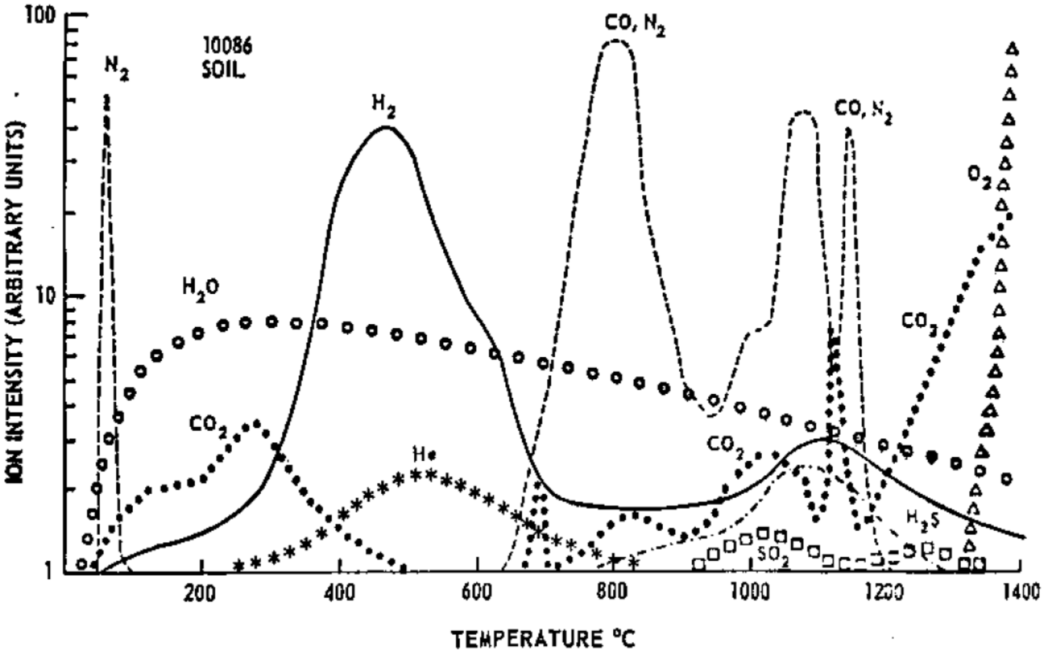

Fig. 1 Gas release rate vs. temperature for Apollo 11 soil sample 10086 [14]

Experimental results on the release of gases from Apollo sample 10084 indicate that about 50% of embedded ^{3}He is released by 500 °C and 95% is released by 800 °C [15]. This release pattern is shown in Fig. 2.

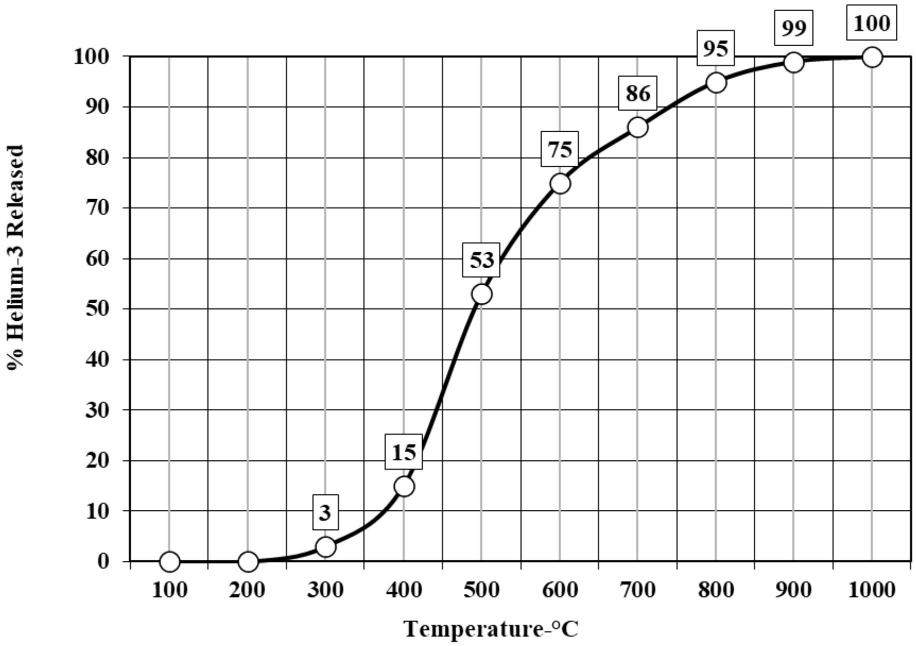

Fig. 2 Thermal release of ^{3}He (% of total released) vs. Temperature (°C) from Apollo sample 10084 [14]

B. Mark Series

Researchers at the FTI leveraged the Apollo sample gas release experiments to develop lunar ^{3}He miner concepts and designs based on the thermal release of solar wind implanted volatiles. Three successive design iterations of a lunar ^{3}He miner were developed at the FTI: the Mark-I, II, and III (M-1 through M-3)[16]–[18]. The M-2 and M-3 concepts are shown in Fig. 3 and Fig. 4, respectively.

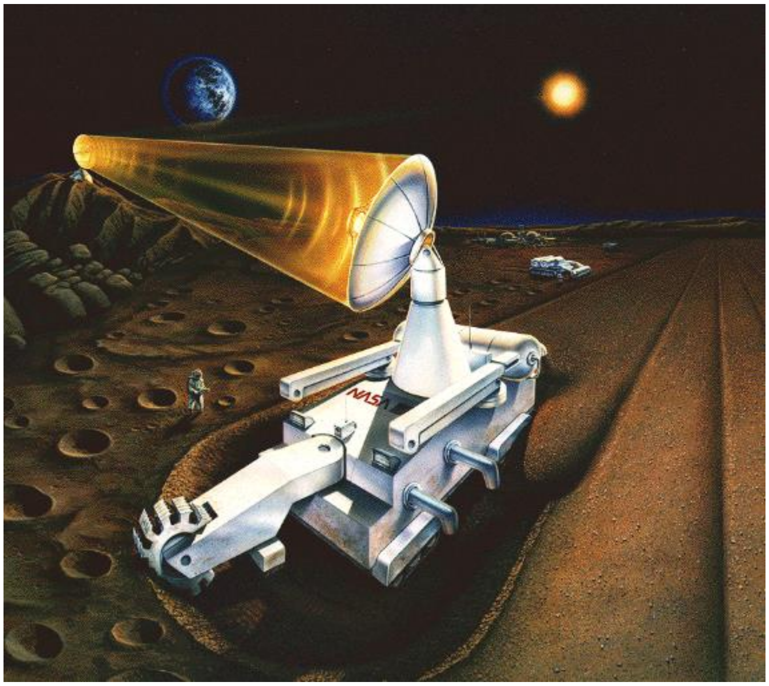

Fig. 3 Illustration of the Mark II ^{3}He lunar volatiles miner (Artwork by J. Andrews) [17]

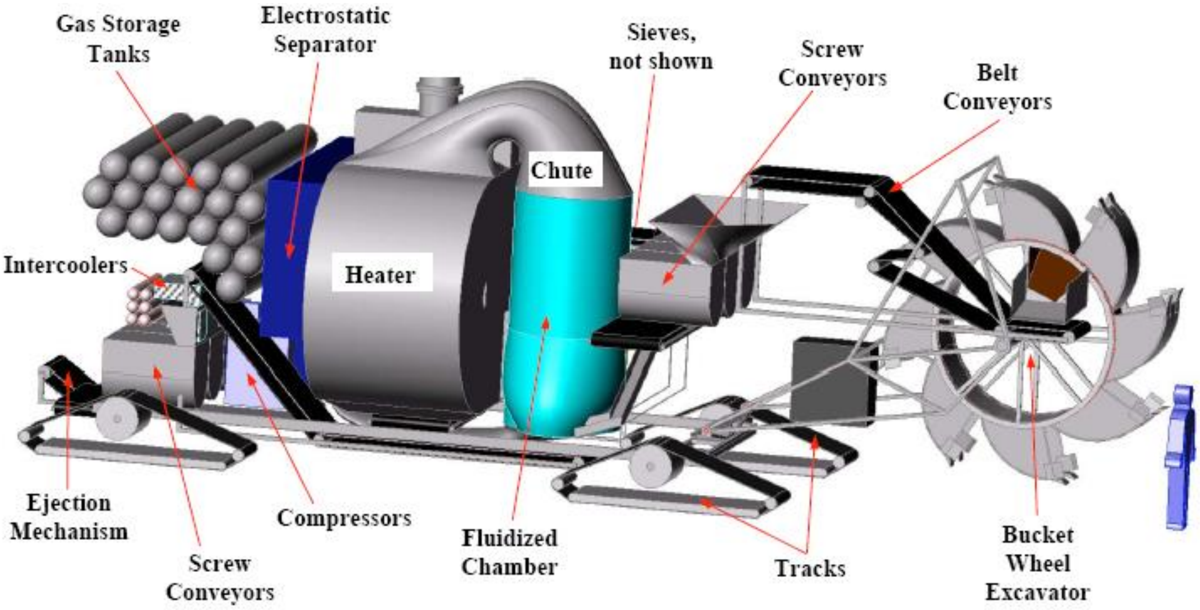

Fig. 4 Interior components of the Mark III helium-3 lunar volatiles miner (Credit: M.E. Gajda) [18]

The most recent design iteration, the M-3, was completed in 2006 [18]. The M-3 was designed to collect 33 kg of ^{3}He per year. The miner would excavate down to a 3 m depth over a 1 km^2 area each year with a 4 m diameter bucket wheel excavator. This would be enough ^{3}He to fuel one ~400 MW fusion power plant per year. The 33 kg/yr collection rate assumes a 10 ppb ^{3}He concentration and that the miner only operates during 90% of the lunar daytime (3942 hours/year). The M-3 is designed to excavate 1258 tonnes/hr, heat 556 tonnes/hr, move at 23 m/hr and consume about 350 kW of electrical power. If the ^{3}He concentration in the undisturbed maria regolith is 20 ppb [19], the collected ^{3}He would be closer to 66 kg/yr. Other solar wind volatiles (H_2, ^{4}He, CO_2, CH_4, N_2, H_2O), which also diffuse out of the regolith with heating, are collected in the M-3 design. These other volatiles are present in the lunar mare region regolith in much higher concentrations than ^{3}He, as seen in Table 1.

Table 1 Volatiles released from heating lunar mare regolith (Apollo 11 sample 10086.16) to 700 °C

Volatile	Mass evolved per tonne of regolith mined (g)*	Mass evolved per kg of ^{3}He evolved (kg)	Mass evolved (tonnes/yr)**
H_2	43	6100	201
^{4}He	22	3100	102
^{3}He	0.007	1	0.066
H_2O	23	3300	109
N_2	4.0	500	16.5
CH_4	11	1600	53
CO	13.5	1900	63
CO_2	12	1700	56
*After beneficiation, 450 kg of regolith is heated			
** With 20 ppb and 1258 tonnes/hr excavation			

The internal pressure of the miner is set to be primarily solar wind evolved hydrogen at 15 kPa. Inside the miner, regolith is beneficiated through a series of sieves, screw conveyors and a fluidized bed to only heat particles smaller than 100 µm. The chosen size cutoff reflects the fact that ~90% of the helium embedded in Apollo 11 sample 10084 was in particles with grain sizes smaller than 100 µm [12]. The sub-100 µm regolith particles enter a heating system where the volatiles are evolved by diffusion out of the regolith. A schematic of the path of regolith and evolved solar wind volatiles (SWV) through the M-3 is shown in Fig. 5.

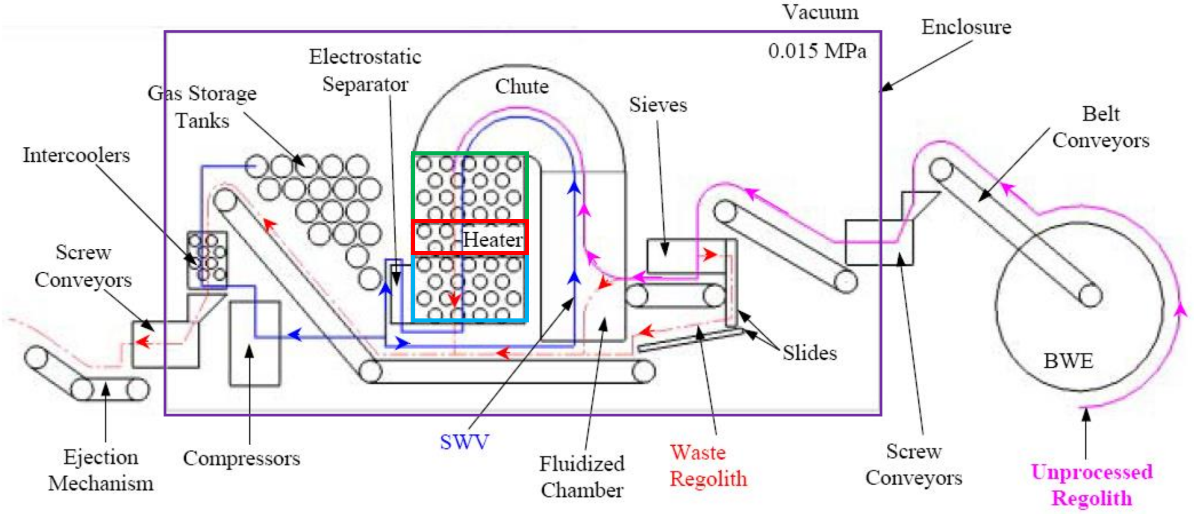

Fig. 5 This regolith and volatile flow schematic illustrates how the Mark-III would collect ^{3}He and other solar wind volatiles. It should be noted that the waste regolith is an integral part of the heater, as it acts to preheat the incoming regolith fines prior to the main section of the heater (shown in red outline) (Credit: M.E. Gajda) [18]

The Mark series miner designs use a moving-bed counter-flow, staged heat pipe heat exchanger (HPHX) with a solar thermal heat source. Gravity drives the moving bed flow of regolith through the heater. Concentrated solar energy is transferred to the heater from a 10 m diameter solar collector, which is designed to receive reflected light from a larger 110 m diameter heliostat. The heating system heats the <100 µm regolith particles up to 700 °C from an expected average inlet temperature of 30 °C. In this design, heat is continuously recuperated from the processed (heated to 700 °C) regolith, before it is ejected from the miner. The collector must provide 12.3 MW to heat 157 kg/s of regolith, assuming an energy recovery efficiency of 85% [16]. Without any energy recovery, this regolith processing would require 82 MW and a much larger and more massive heliostat and solar collector system.

Heat pipes were chosen for their ability to transfer heat nearly isothermally. Each heat pipe is hermetically sealed and has an evaporator and condenser section. A working fluid within each heat pipe is heated from a liquid state to a vapor state at the evaporator section. In the case of the miner's HPHX, the heated and volatile depleted regolith heats the vaporizing working fluid within the heat pipes. At the condenser section of each heat pipe, the working fluid is cooled from a vapor state back to a liquid state by the incoming cold and volatile rich regolith. The HPHX was designed with 21,500 u-shaped heat pipes, each being 1.5 cm outer diameter with 1 m long condenser and evaporator sections. The working fluid in the heat pipes varies with position in the heating system. Water can be used in the lowest temperature rows (stages) of heat pipes. Working fluids that can operate at higher temperatures would be needed for the remaining stages. Mercury, potassium and sodium are used to achieve the needed temperature progression. Each stage of heat pipes operates at the boiling point for the working fluid within, for the selected heat pipe vapor pressure. The heat pipes with water as the working fluid have copper as the pipe material while all the other heat pipes use stainless steel. The concept of the heat pipe heat exchanger for the Mark series of ^{3}He and lunar volatiles miners is shown in Fig. 6 where the heat pipe condenser sections are the same as the preheater section and the evaporator sections are the same as the recuperator section shown. The estimated regolith temperature, as it flows downward through the heater (at an effective velocity of 15 cm/s), is also shown in Fig. 6. The preheater and recuperator sections of the HPHX have 91 stages of 118 heat pipes per stage. The columns of heat pipes are spaced 1.7 cm apart (pipe center to center) and the rows are offset to achieve a 60° triangular pitch arrangement throughout the heat exchanger. The HPHX is approximately 5 m in length, 2 m in width and 3 m in height with two equally sized flow enclosures. The HPHX is estimated to be about 9 tonnes.

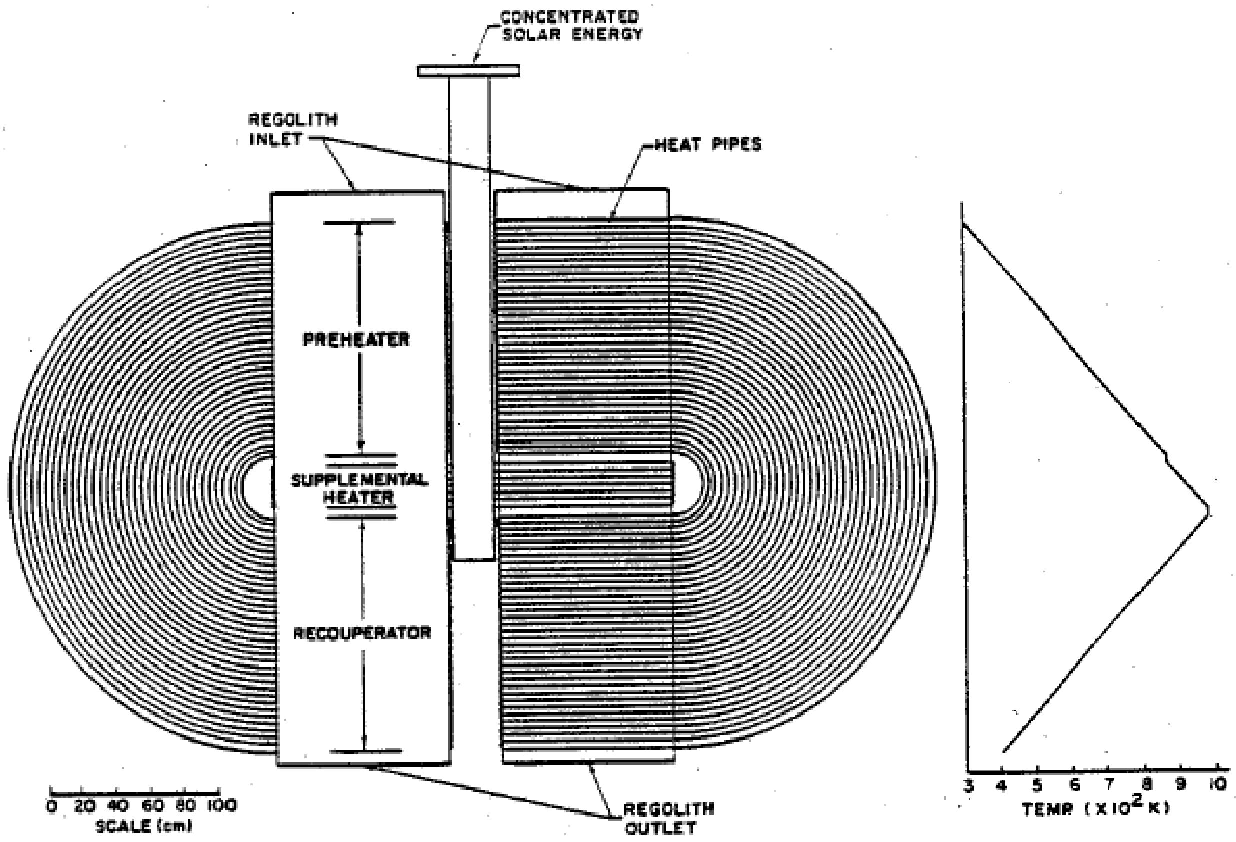

Fig. 6 Illustration of the heat pipe heat exchanger designed for the Mark series of helium-3 lunar volatiles miners. The system is scaled to heat 157 kg/s of regolith from 30 °C up to 700 °C and recover 85% of waste regolith heat. The flow is separated into two enclosures. [16]

The M-3 design uses six staged compressors and three intercoolers to store the SWV in tanks at the rear of the miner. Water and carbon dioxide are to be stored as liquid in one set of tanks while the other SWV are stored in gas tanks at 20 MPa. These tanks are to be collected by another vehicle for future gas separation and isotopic separation processing on the Moon. The various other systems needed for the operation of the miner like its mobility system, radio frequency power beaming subsystem, fuel cells, and waste regolith ejection system are described in much more detail in [16–18].

C. Spiral

The spiral mining concept could potentially eliminate the need for a transport vehicle to collect and carry tanks to and from a central processing facility [20]. A mobile central station could be integrated with a mobile miner through a tether or support arm (possibly a smaller version of the M-3) to directly transport the evolved SWV to a refining facility inside the central station. The tethered miner could receive electrical power to operate its excavation, mobility, conveyor and refining systems through the support arm. The spiral mining concept could increase operational flexibility due to the use of multiple independent processing stations. The concept could also potentially reduce the complexity and mass of each mobile miner. The feasibility of this approach depends on whether the support arm for the miner could operate as desired. More detailed design around the required bearing(s) at the central station, the structural support for the miner-to-station support arm, and the gas and power transfer processes would be needed to further evaluate the concept. Schematics of the conceptual spiral mining architecture and the elements of an associated central processing station are shown in Fig. 7.

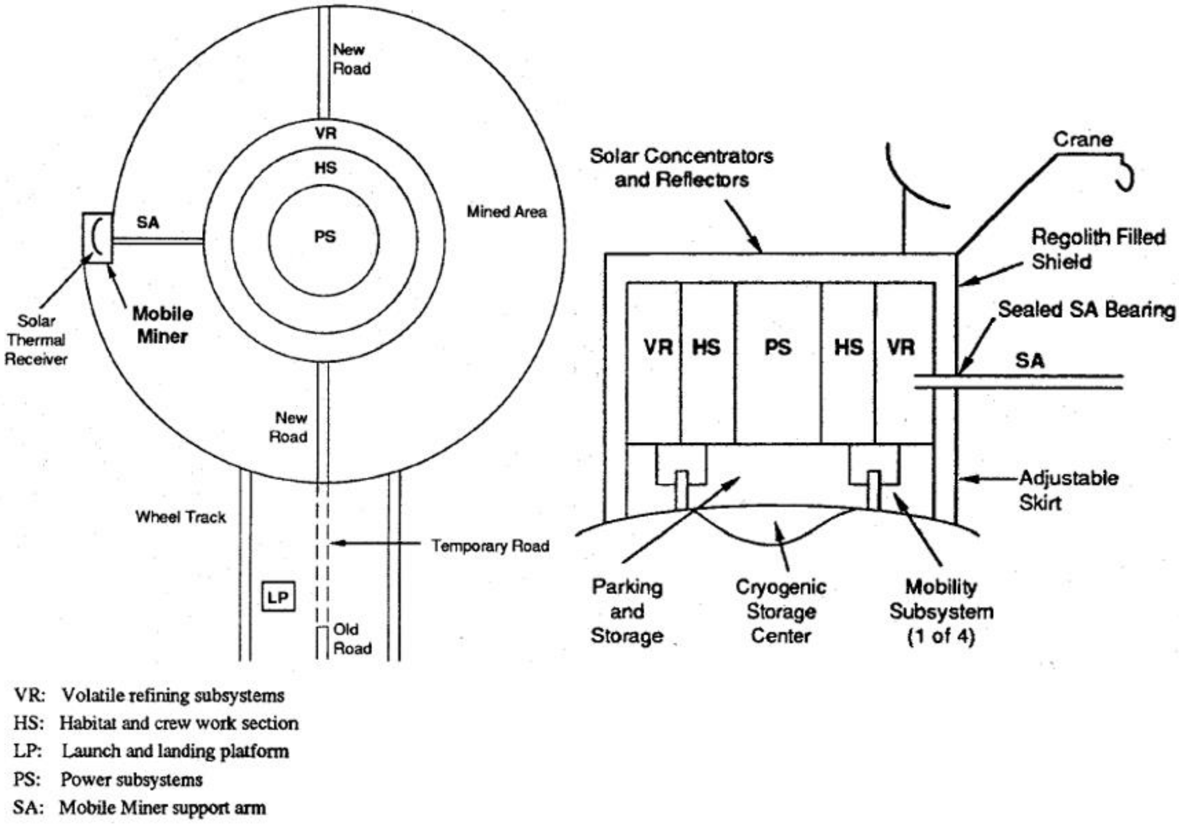

Fig. 7 Schematic of central processing station for spiral mining concept (Credit: H.H. Schmitt) [20]

D. In-Situ Volatile Release

Acquiring 33 kg of ^{3}He (enough to operate one 400 MW D^{3}He fusion power plant) requires that nearly five million tonnes of regolith be excavated (assuming 10 ppb ^{3}He) [17], [21]. Large terrestrial coal mining machines, like the TAKRAF SR 8000 series, can excavate over 16,000 tonnes/hr of overburden (more than 10 times the excavation rate of the Mark miners) [22]. This suggests that, eventually, it would feasible to mine millions of tonnes of regolith annually per miner (or per fusion power plant) once the long-term effects of operating excavating equipment on the lunar environment are determined. The in-situ volatile release concept is an alternative concept for lunar ^{3}He acquisition that requires no regolith to be displaced. The concept is to apply heat to an area of regolith under an impermeable enclosure and pump the evolved volatiles into a tank. This could be done on a mobile platform that only heats the surface, shown in Fig. 8 [23].

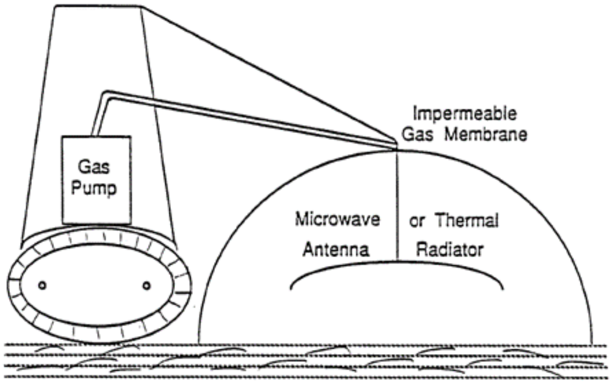

Fig. 8 Sketch of an in-situ gas evolution device for collecting lunar volatiles (Credit: Y.T. Li and L.J. Wittenberg) [23]

The in-situ volatile release concept could also be done with a domed enclosure structure that would need to be moved each lunar day [24]. This domed structure concept is shown in Fig. 9.

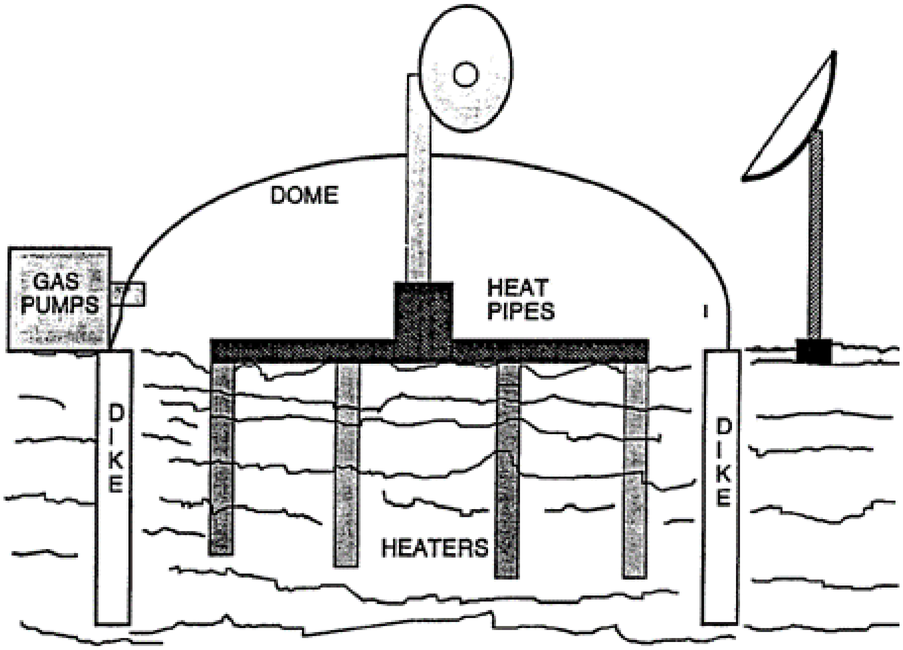

Fig. 9 Conceptual design of an in-situ volatile collection with a stationary enclosure, heaters powered by solar energy and an underground barrier (dike) to prevent gas loss laterally (Credit: L.J. Wittenberg) [24]

In the domed enclosure concept, an underground gas barrier (dike) is set up to hold a 101 kPa hydrogen atmosphere under the domed enclosure. Fifty cm outer diameter solar thermal powered heating elements, heated to 800 °C by a solar collector and heliostat, are buried 3 m deep into the subsurface. It was estimated that the coldest regolith between the heating elements reaches about 627 °C after 320 hours of heating during the lunar day [24]. The evolved volatiles, including about 80% of the embedded ^{3}He, diffuse through and out of the regolith surface into the domed and above-surface region. The volatiles are then pumped out of the enclosure. If the domed structure is moved after every lunar day (13 times/Earth year), three 100 m diameter enclosed areas, could yield 30 kg of ^{3}He per year (10 ppb ^{3}He), approximately as much as the M-3 miner. Each domed enclosure would include 8,200 m^2 of impermeable barrier material, 7,800 embedded heat pipes, a solar collector-heliostat system, core-drive boring machines, gas separation radiators, a helium isotopic separation system and service vehicles and/or robots to operate and move the entire structure. The mass of the entire mining operation was estimated at 174 tonnes, not including the crew accommodations required. The mass of regolith disturbed for this operation was estimated to be about 5 tonnes or one millionth of that required for the excavator designs [24]. In contrast, an entire mining operation based on the M-3 miner was estimated to have a mass of ~50 tonnes and would require that 5 million tonnes of regolith be excavated.

III. Helium Extraction Experiments

Experiments done in 2018 at the FTI, in collaboration with NASA KSC's Swamp Works, investigated the flow induced agitation release of helium from JSC-1A lunar regolith simulant within a heat pipe heat exchanger [25]. The Experimental approach included the implantation of helium-4 into batches of lunar regolith simulant, the processing of the implanted simulant by flowing it through a heat pipe heat exchanger and, lastly the analysis of samples of the implanted simulant for its remaining helium content with a vacuum heating and mass spectrometer system. The experimental results constituted the first measurements and quantification of the amount of agitation loss from helium implanted regolith simulant in a heat pipe heat exchanger. The amount of helium agitation loss increased with regolith simulant flow rate.

A. Solar Wind Implanter

A system called the Solar Wind Implanter (SWIM) was developed in 2015 to implant batches of up to 2 kg of regolith simulant with helium [26], [27]. The aim of the SWIM device design was to implant helium ions at solar wind speeds (300- 900 km/s, average of ~450 km/s) into 2 kg batches of <100 µm lunar regolith simulant. SWIM used ^{4}He in place of ^{3}He, as ^{4}He has nearly identical diffusion characteristics as ^{3}He and is far more readily available for experimental work. In the SWIM system, regolith particles are implanted when they are dropped through a flux helium ions that are electrostatically accelerated, as illustrated in Fig. 10. SWIM operates inside of a vacuum chamber that is back filled to a prescribed pressure of helium.

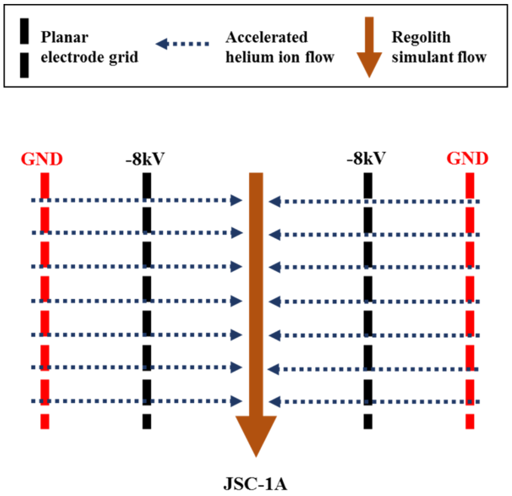

Fig. 10   Concept of helium implantation into regolith simulant in the SWIM system [27]

The electrostatic potential that accelerates the helium ions is produced with two sets of parallel electrode grids. The cathode grids are held at a negative potential relative to the grounded anode grids. The flow of simulant through the SWIM system is controlled by a 3D printed rotary valve feeder that is mounted above the grids. The feeder and the other major components of the SWIM system are shown in Fig. 11.

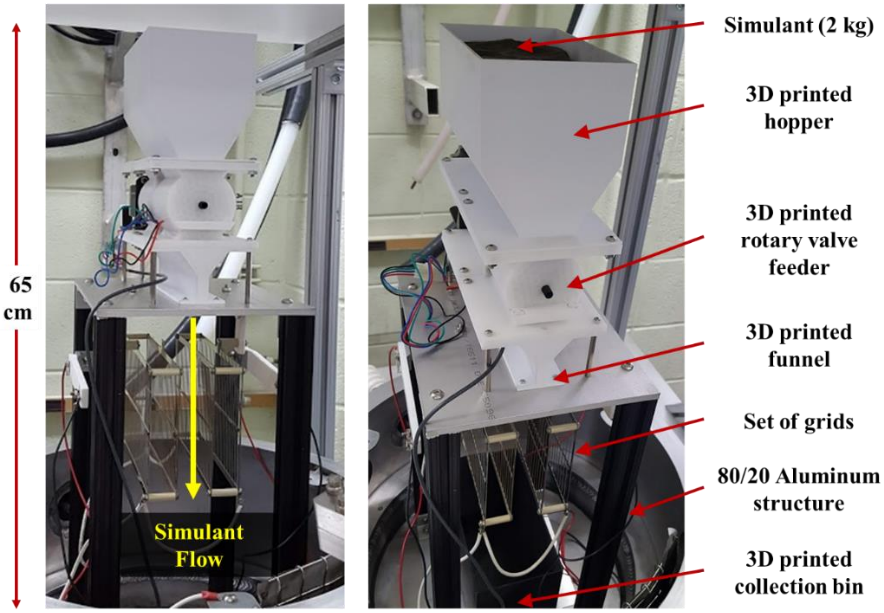

Fig. 11   The path of simulant flow through the SWIM system (left) and the major components of the SWIM system (right) [25]

An image from inside of the SWIM vacuum chamber, during one of its first an implantation runs, is shown in Fig. 12.

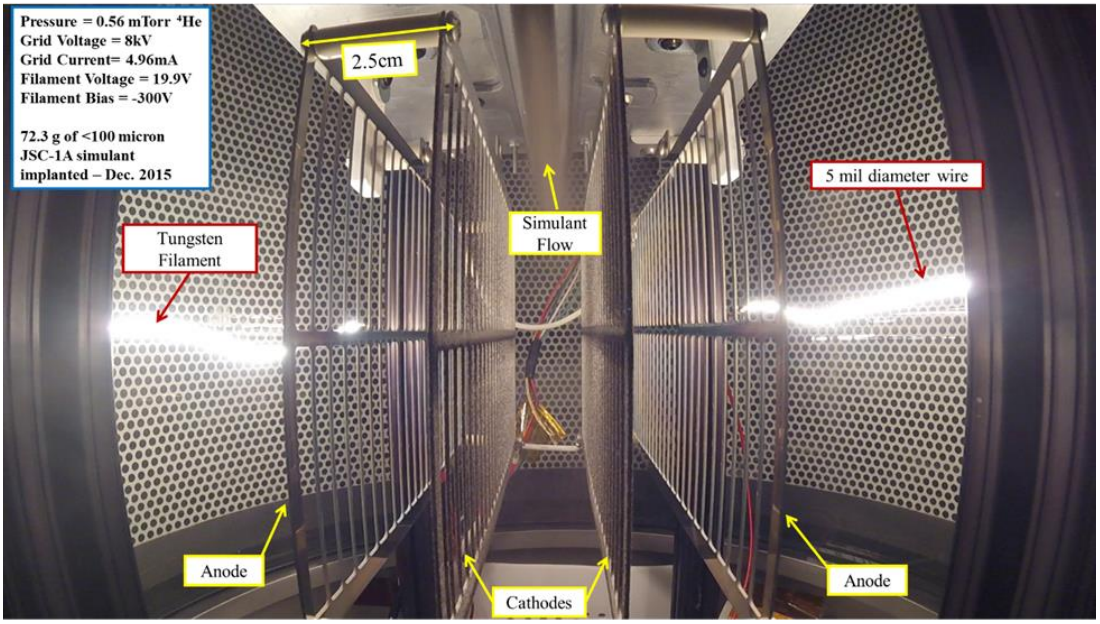

Fig. 12 Image from inside of the SWIM vacuum chamber (first chamber at NASA KSC Swamp Works – ESPL) during an implantation run at 0.6 mTorr ^{4}He and -8 kV cathode potential [27]

B. Helium Extraction & Acquisition Testbed

The Helium Extraction & Acquisition Testbed (HEAT) was designed to test how ^{3}He can be released from lunar regolith in future lunar miner systems due to agitation and heating [28], [29]. HEAT includes passive and active flow components along with passive and active heating components (heat pipes and cartridge heaters). The HEAT system is shown in Fig. 13. HEAT mainly consists of a HPHX (that can have variable heating element arrangements), components to store and flow simulant through the HPHX, and instrumentation to measure the mass flow rate of simulant and the temperature at key positions in the system. The HPHX is a 5-stage counter flow heat exchanger made of U-shaped heat pipes that are wrapped over 4 rows of cartridge heaters. The heat pipes and cartridge heaters are held in place by a 304 stainless steel enclosure that has an insulating radiative barrier around it. The HPHX is shown in Fig. 14 along with its instrumentation: 14 type k thermocouple probes and an infrared thermopile array camera. A HEAT HPHX thermal model was developed to calculate the needed input power for a given HPHX configuration and regolith maximum temperature requirement. Key outputs of the model include the heat pipe temperature, heat transfer, and regolith temperature as function of position through the HPHX. More details of the model can be found in [25].

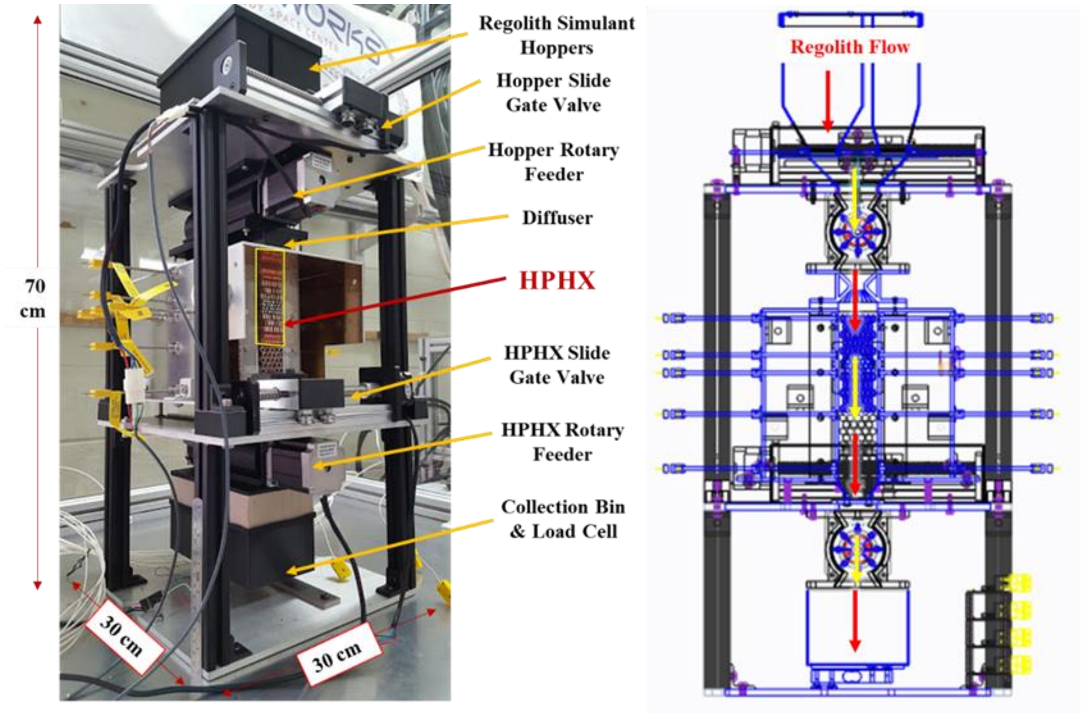

Fig. 13 HEAT system components (left) and the path of regolith flow through the system (right) [25]

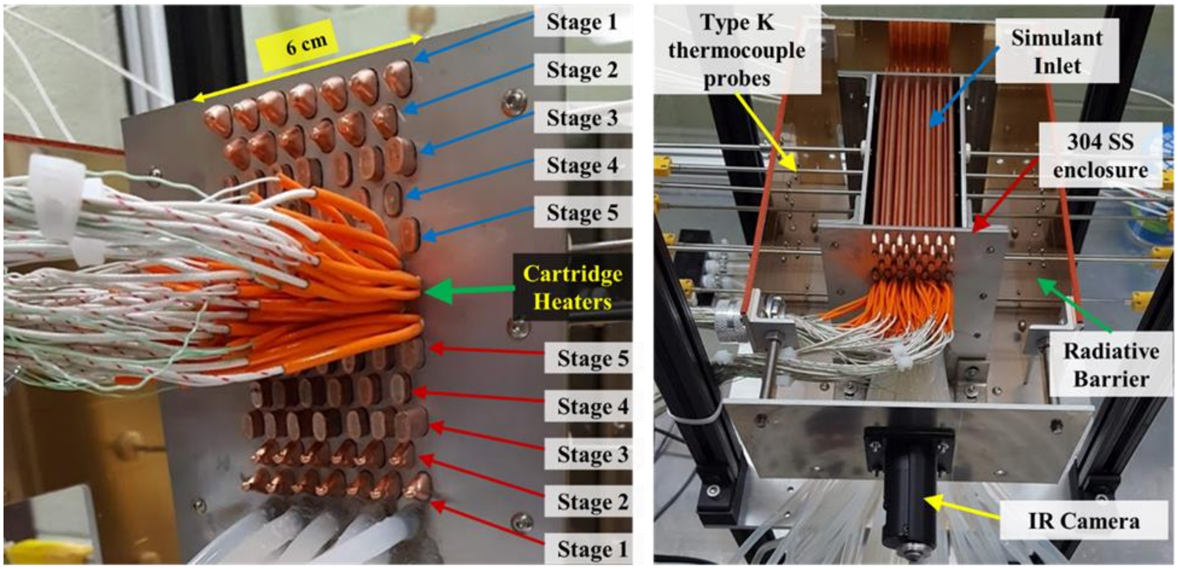

Fig. 14 The HEAT HPHX front view is show on the left with the heat pipe stages numbered. The HPHX enclosure, insulation and thermal instrumentation is shown on the right [25]

C. Helium Release Experimental Results

A Sample Concentration Analysis (SCAN) system was constructed to measure the concentration of helium in SWIM implanted regolith simulant and HEAT processed regolith simulant. SCAN used a 100 cm^3 porcelain crucible, a 300-watt 8 mm outer diameter cartridge heater, two type k thermocouple probes and a vacuum system instrumented with a Residual Gas Analyzer (RGA). The crucible is filled with 20 g of simulant during tests. The cartridge heater and its controller are used to increase the temperature of the simulant in isochronal (same duration) steps up to 600 °C. The components of the SCAN system are shown in Fig. 15.

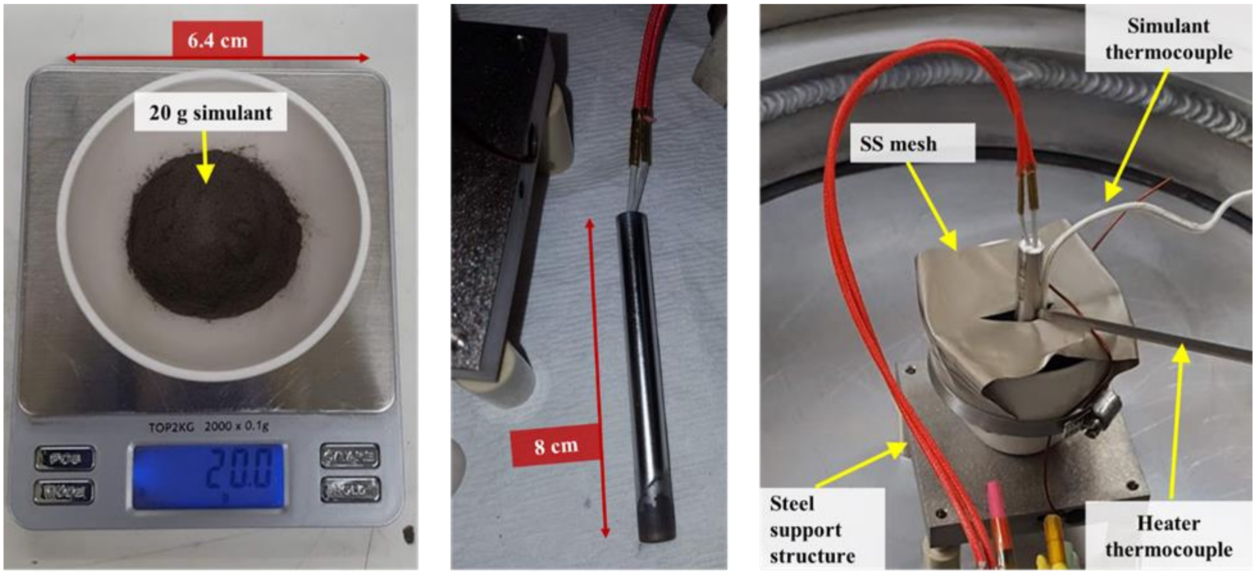

Fig. 15 Component of the SCAN system: crucible with 20 g of simulant (left), 8 mm O.D. x 80 mm length cartridge heater (center), assembly with thermocouples stainless steel mesh covering (right) [25]

The raw ^{4}He partial pressure vs. time data from the RGA is shown for a 20 g sample of SWIM implanted regolith simulant in Fig. 16. The peaks show the nature of how more deeply implanted helium is quickly released with each step increase in temperature.

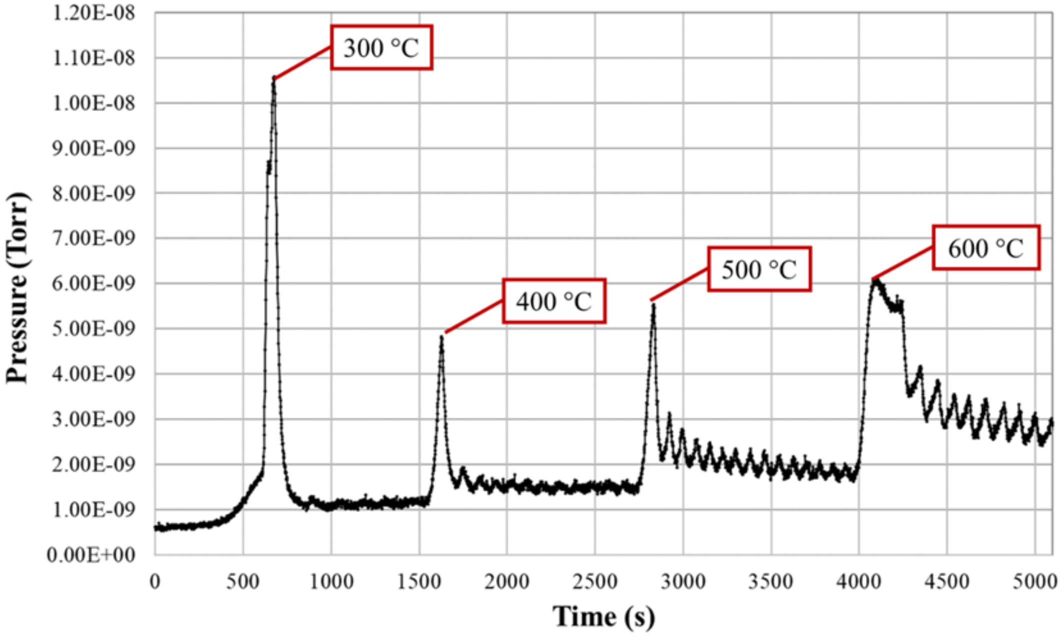

Fig. 16 Helium-4 partial pressure vs. time for a 20-gram sample of implanted simulant heated from 150 to 600 °C. The callouts indicate the temperature associated with the major pressure peaks [25].

The release of ^{4}He from SWIM implanted JSC-1A regolith simulant, shown in Fig. 17 is similar to that of Apollo samples (in particular Apollo 10084) up to 600 °C.

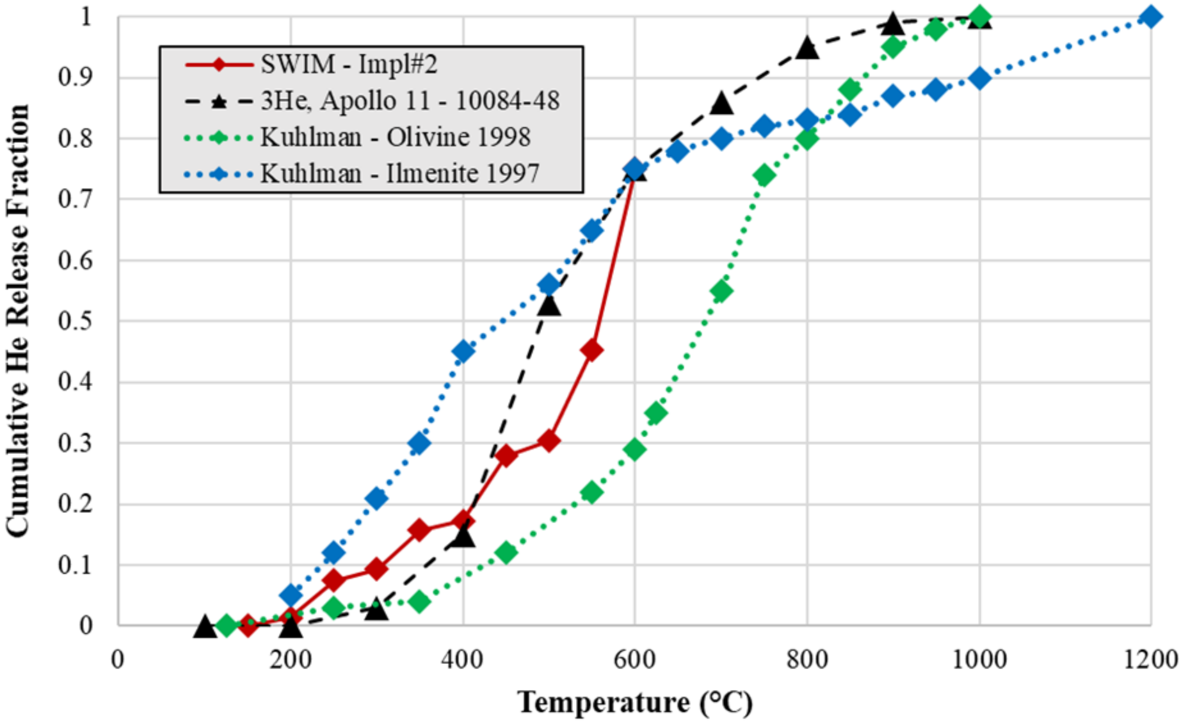

Fig. 17 Cumulative helium release fraction vs. temperature for a sample of SWIM implanted simulant, an Apollo soil sample, and two implanted lunar mineral analogs [9], [15], [30]

Two batches of SWIM implanted simulant were run through the HEAT HPHX. The first batch was processed at 1.5 g/s and the second at 9.0 g/s. The remaining ^{4}He concentrations in the implanted simulant (after implantation) for the 1.5 g/s and 9 g/s samples were 2.7 ppb and 2.1 ppb, respectively. The remaining ^{4}He concentrations in the simulant batches after passing through HEAT, when corrected for the average control ^{4}He concentration, were 0.7 ppb and 0.1 ppb. Normalizing the remaining implanted ^{4}He concentration by the average implanted sample concentration shows that only 29% of the implanted ^{4}He remained for the 1.5 g/s sample, while 4% of the implanted ^{4}He remained for the 9 g/s sample. This result is illustrated in Fig. 18. The implanted JSC-1A simulant samples that were implanted with ^{4}He and run through the HPHX indicated that, 70% and 96% of the implanted ^{4}He was removed at the flow rates of 1.5 g/s and 9 g/s, respectively. This regolith was not heated above room temperature, yet the amount of helium released corresponds to the ^{3}He evolution during heating of lunar soil samples to about 500 °C. The amount of heating required to extract ^{3}He from lunar regolith could be significantly reduced, if not even completely removed, if agitation can be leveraged as a primary method of releasing ^{3}He in a system that extracts and recovers the gas. It should be noted that the conditions of the SWIM implantation only replicate a portion of the solar wind energy spectrum and that the surface structure of the JSC-1A regolith simulant used cannot fully replicate the surface conditions of real lunar regolith.

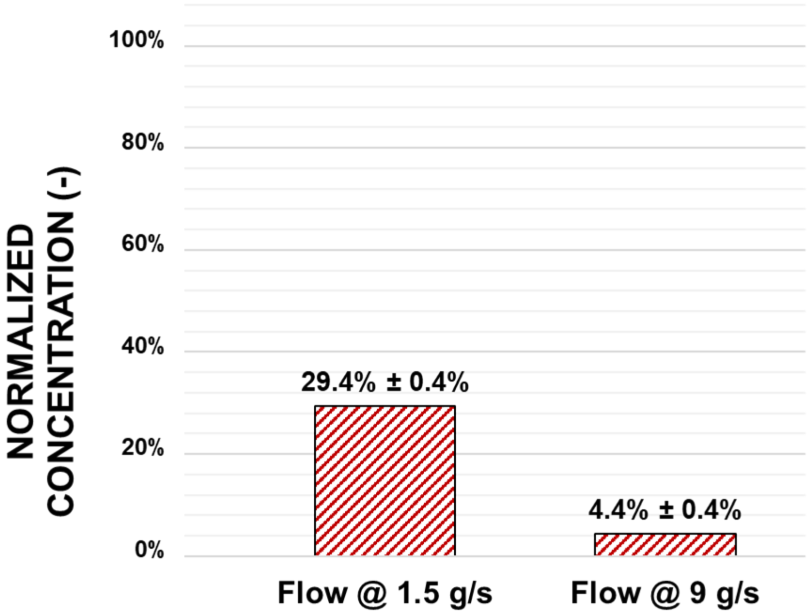

Fig. 18 Retained ^{4}He in SWIM implanted simulant run at two speeds through the HEAT system [25]

IV. In-Situ Resource Utilization Synergies

Helium-3 is one of many valuable lunar resources, and its extraction could occur with the extraction of other valuable lunar volatiles [21]. This connection could provide an opportunity to collect these other resources if lunar ^{3}He is mined at scale. Perhaps this connection may allow for the development of ^{3}He mining technology within the context of the acquisition of other lunar volatiles. Lunar settlements, in-space fuel depots, and the emerging space tourism industry will require significant amounts of water and oxygen to support their envisioned crews and operations [21,31]. In the more near term, a pilot operation to demonstrate the ability to collect 15 tonnes water for liquid oxygen/liquid hydrogen propellant from 5% water rich regolith may require ~400 tonnes of regolith to be excavated [33], [34]. This type of pilot scale operation could also demonstrate the ability to extract about 6 g of ^{3}He, assuming the ^{3}He concentration in permanently shadowed regions on the Moon is similar to that of equatorial regions. A subsystem to collect ^{3}He (through agitation) could be added to water and oxygen extraction plants, excavators and conveyors. This somewhat passively collected ^{3}He could be separated and stored on the Moon for eventual transport to Earth.

Acknowledgments

The author would like to thank Professor Gerald Kulcinski, Professor John Santarius, and Apollo 17 Astronaut Dr. Harrison H. Schmitt of the FTI for their guidance in developing the experimental work discussed in this paper. The author would also like to thank Dr. James Mantovani of NASA Kennedy Space Center for his support in developing the experimental systems discussed.

References

[1] Wittenberg, L. J., Santarius, J. F., and Kulcinski, G. L. “Lunar Source of 3He For Commercial Fusion Power.” *Fusion Technology*, Vol. 10, 1986, pp. 167–178.

[2] Wittenberg, L. J. “Terrestrial Sources of Helium-3 Fusion Fuel- A Trip to the Center of the Earth.” *Fusion Technology*, Vol. 15, 1989, p. 1108.

[3] Kulcinski, G. L. Fusion Fuel Resources. 2012.

[4] Wittenberg, L. J., Cameron, E. N., Kulcinski, G. L., Ott, S. H., Santarius, J. F., Sviatoslavsky, I. N., Sviatoslavsky, G. I., and Thompson, H. E. “A Review of Helium-3 Resources and Acquisition for Use as Fusion Fuel.” *Fusion Technology*, Vol. 21, 1992, pp. 2230–2253.

[5] British Petroleum (BP). *BP Statistical Review of World Energy*. 2018.

[6] 28th IAEA Fusion Energy Conference (FEC 2020) (10-15 May 2021): Overview of C-2W: High Temperature, Steady-State Beam-Driven Field-Reversed Configuration Plasmas · Indico for IAEA Conferences (Indico). https://conferences.iaea.org/event/214/contributions/17043/. Accessed Oct. 12, 2021.

[7] Geiss, J. Solar Wind Composition and Implications about the History of the Solar System. 1993.

[8] National Oceanic and Atmospheric Administration. ACE Real-Time Solar Wind | NOAA / NWS Space Weather Prediction Center. *www.swpc.noaa.gov*. https://www.swpc.noaa.gov/products/ace-real-time-solar-wind. Accessed Sep. 2, 2018.

[9] Kuhlman, K. R. *Trapping and Diffusion of Helium in Lunar Materials*. 1998.

[10] Eberhardt, P., Geiss, J., Graf, H., Grögler, N., Mendia, M. D., Mörgeli, M., Schwaller, H., Stettler, A., Krähenbühl, U., and von Gunten, H. R. "Trapped Solar Wind Noble Gases in Apollo 12 Lunar Fines 12001 and Apollo 11 Breccia 10046." *Proceedings of the Third Lunar Science Conference, vol. 3, p. 1821 - 1856*, Vol. 3, 1972, pp. 1821–1856.

[11] Hintenberger, H., Weber, H., Voshage, H., Wanke, H., Begemann, F., and Wlotzka, F. Concentrations and Isotopic Abundances of the Rare Gases, Hydrogen and Nitrogen in Apollo 11 Lunar Matter. 1970.

[12] Cameron, E. N. *Titanium in Lunar Regolith and Its Use in Mining Site Selection*. 1987.

[13] Swindle, T. D., Glass, C. E., and Poulton, M. M. *Mining Lunar Soils for 3He - TM-90/1*. 1990.

[14] Gibson Jr., E. R., and Johnson, S. M. Thermal Analysis-Inorganic Gas Release Studies of Lunar Samples. 1971.

[15] Pepin, R. O., Nyquist, L. E., Phinney, D., and Black, D. C. Rare Gases in Apollo 11 Lunar Material. 1970.

[16] Sviatoslavsky, I. N., and Jacobs, M. K. Mobile Helium-3 Mining and Extraction System and Its Benefits Toward Lunar Base Self-Sufficiency. 1988.

[17] Sviatoslavsky, I. N. The Challenge of Mining He-3 on the Lunar Surface: How All the Parts Fit Together. 1993.

[18] Gajda, M. *A Lunar Volatiles Miner*. University of Wisconsin-Madison, M.S. Thesis, 2006.

[19] Schmitt, H. H. Return to the Moon. In *Return to the Moon*, Praxis, 2005, p. 89.

[20] Schmitt, H. H., Kulcinski, G. L., Sviatoslavsky, I. N., and Carrier, W. D. "Spiral Mining for Lunar Volatiles." *Space 92, The Third International Conference on Engineering, Construction, and Operations in Space, 31 May-4 June 1992, Denver CO Also: Wisconsin Center for Space Automation and Robotics Technical Report (WCSAR-TR) AR3-9203-1*, 1992, p. 6.

[21] Kulcinski, G. L., Sviatoslavsky, I. N., and Wittenberg, L. J. Impact of Lunar Volatiles Produced During 3He Mining Activities. 1996.

[22] Tenova TAKRAF GmbH. TAKRAF GmbH - Bucket Wheel Excavators. *www.takraf.com/en*. http://www.takraf.com/en/products/miningequipment/bucketwheelexcavator.htm. Accessed Aug. 30, 2013.

[23] Li, Y. T., and Wittenberg, L. J. "Lunar Surface Mining for Automated Acquisition of Helium-3: Methods, Processes, and Equipment." *Wisconsin Center for Space Automation and Robotics Technical Report (WCSAR-TR) AR3-8809-2*, 1988, p. 4.

[24] Wittenberg, L. J. In-Situ Extraction of Lunar Soil Volatiles. 1993.

[25] Olson, A. D. S. *Helium Extraction through Agitation from Lunar Regolith Simulant in a Heat Pipe Heat Exchanger*.

[26] Olson, A. D. S., Kulcinski, G. L., and Santarius, J. F. Helium Ion Implantation into JSC-1A Lunar Regolith Simulant for a Volatiles Extraction Experiment. 2015.

[27] Olson, A. D. S., Kulcinski, G. L., Santarius, J. F., and Mantovani, J. G. Helium Implantation Into JSC-1A Lunar Regolith Simulant for Testing Volatile Extraction Technologies. 2016.

[28] Olson, A. D. S., Kulcinski, G. L., Santarius, J. F., and Mantovani, J. G. Granular Flow and Heat Transfer Modeling for the Helium Extraction and Acquisition Testbed. 2018.

[29] Olson, A. D. S., Santarius, J. F., and Kulcinski, G. L. "Design of a Lunar Solar Wind Volatiles Extraction System." *Proceedings of the Wisconsin Space Conference*, Vol. 1, No. 1, 2015. https://doi.org/10.17307/wsc.v1i1.100.

[30] Kuhlman, K., and Kulcinski, G. L. Helium Isotopes in the Lunar Regolith - Measuring Helium Isotope Diffusivity in Lunar Analogs. In *Moon: Prospective Energy and Material Resources*, Springer Praxis, 2012, pp. 22–56.

[31] Metzger, P. T., Muscatello, A., Mueller, R. P., and Mantovani, J. "Affordable, Rapid Bootstrapping of the Space Industry and Solar System Civilization." *Journal of Aerospace Engineering*, Vol. 26, No. 1, 2013, pp. 18–29. https://doi.org/10.1061/(ASCE)AS.1943-5525.0000236.

[32] Kleinhenz, J., Grc, N., Paz, A., and Jsc, N. "Case Study for Lunar ISRU Systems Utilizing Polar Water."

[33] Linne, D. L., Kleinhenz, J. E., Trunek, A., Hoffman, S., and Collins, J. Extraction of Volatiles from Regolith or Soil on Mars, the Moon, and Asteroids. 2017.