Mining Helium-3 on the Moon

by Aaron Olson

This is an edited transcript of the speech presented by Dr. Aaron Olson to the Schiller Institute conference in New York, "Mankind as a Galactic Species: The Necessary Alternative to War," on October 5, 2019. The full video of the conference of is available here. Subheads have been added. For additional coverage of the conference, see EIR, Vol. 46, No. 40, Oct. 11, 2019.

An exhibit of Aaron Olson's research for an efficient device for extracting helium-3 from the surface of the Moon, won First Prize in the "Group, Graduate" category at the University of Wisconsin-Madison's Engineering Expo 2015. Olson (third from left) is seen here with one of his processing chambers and his collaborators in creating the exhibit (l. to r.), Alex Strange, Tashi Atruksang, and Abe Megahed.

Good afternoon, everyone! It's my pleasure to be here today with you all to celebrate the International Observe the Moon Day. My name is Aaron Olson; I graduated with my PhD from the University of Wisconsin, Madison, in 2018. My thesis topic was research to develop technology to harvest helium-3 from lunar soil.

I'll start with why we're interested in helium-3 in the first place. As others have brought up already during today's conference, helium-3 could be a part of fusion fuel in reactors that could help us bring more energy across the world, and offer us opportunities to bring this sort of power production into space to help us with more exploration, to find out more of what's going on in our own Solar System and potentially beyond, in the future.

Figure 1 is a reactor at a facility for TriAlpha Energy [now TAE Technologies—ed.]. I like to show this image because it illustrates that technology around fusion isn't just something on paper, or something that's in the imagination of people across the world. There are companies right now who have been funded by billionaires and large organizations that are developing this technology right now. This is one of the potential reactors that TriAlpha is working on. This particular device is capable of "burning" or fusing helium with deuterium to produce fusion power. It does it at scales that aren't relevant for power plants today, but it's the sort of technology that 10-15 years from now could allow us to have reactors.

So, when helium-3 is fused with deuterium, or when helium-3 is fused with helium-3, you get reactions that

FIGURE 1

^{3}He Could Be a Significant Future Fusion Fuel

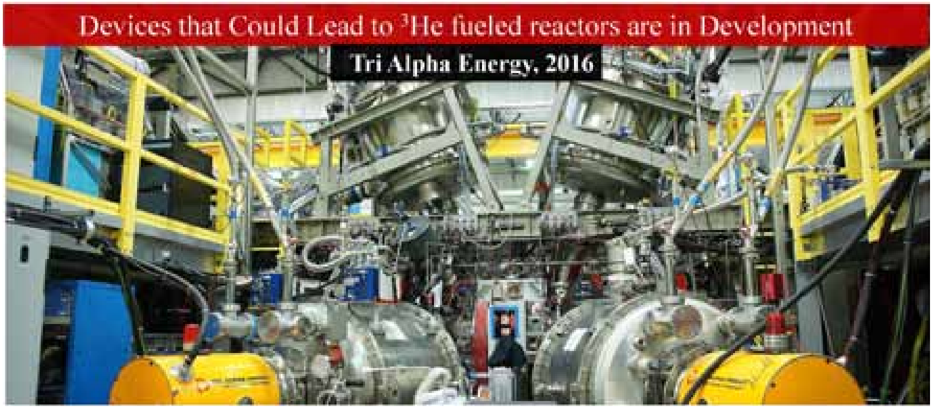
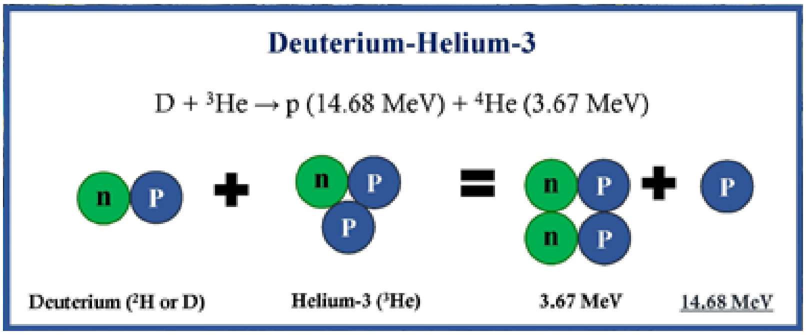


FIGURE 2



produce high-energy protons (**Figure 2**). As opposed to deuterium that's fused with tritium, as what the ITER [International Thermonuclear Experimental Reactor] project is proposing, and many other more traditional approaches for fusion have proposed, this high-energy proton release or reaction product allows for the energy to be directly converted into electricity, instead of into heat, which then could be used in a Rankine cycle or any other thermal cycle to produce power.

This means that not only is this a more efficient way of producing power for power plants across the world. On top of that, with the reduction of the neutrons that would be produced in a deuterium-tritium power plant, or the neutrons that are produced in fission power plants today, you have a reactor vessel that doesn't become radioactive. So, you get nuclear power without any radioactive waste. That's incredible!

Some Basics of Helium-3

Back to some of the basics around helium-3. Many of you may be wondering where helium-3 originates. It's actually created in the Sun. At all times, the Sun is fusing hydrogen with hydrogen inside of its core; but it's also fusing other things all the time. That's how we get a lot of our heavier isotopes and heavier elements. They're actually created inside of stars. So, helium-3, like many other things, is also created inside of a star.

What happens is, it's emitted from the Sun in something called the solar wind. The solar wind is a flux of charged particles emitting from the Sun at all times. Because it's charged, any body in the Solar System that has a magnetic field around it, deflects this charged flux of particles. Around the Earth, we have a very powerful magnetic field that protects us from a lot of the things that are being emitted not only from our Sun, but from a number of other sources across the Solar System and our galaxy. A number of other bodies across the Solar System also have magnetic fields. On top of that, many bodies have forms of atmosphere. Fortunately for us, we have a very healthy atmosphere that protects us and allows us to live on Earth. All of that blocks out this flux of helium-3 and other charged particles that come from the Sun.

But the Moon has neither a magnetic field nor a substantial atmosphere. So because of that, over the lifetime—4.5 to 5 billion years roughly, the time that the Moon has existed—a tremendous amount of helium-3 has been bombarded onto its surface (see **Figure 3**). A fraction of that still remains today, and is retained in the first 3-5 meters of depth of the lunar surface. Because of the Soviet missions in the 1960s and 1970s, and the Apollo missions in the 1960s and 1970s, we got proof of this. In fact, 360 kilograms of material from the Apollo missions was brought back to Earth. Samples from all of that material that came back were heated up, and in the process of being heated up, gave out not only helium-3, but a number of other volatile gases; proving that helium-3 was one of the elements and isotopes that was within that soil.

One place to get a lot of background on all of this, not only the solar wind part, but also the background on the Apollo samples—the Luna 16, Luna 20, and Luna 24 missions as well that brought back samples that had helium-3—is the book, *Return to the Moon*, by Apollo astronaut Dr. Harrison Schmitt. This came out in 2006,

FIGURE 3

The Moon Could Enable over 1000 Years of ^{3}He Energy

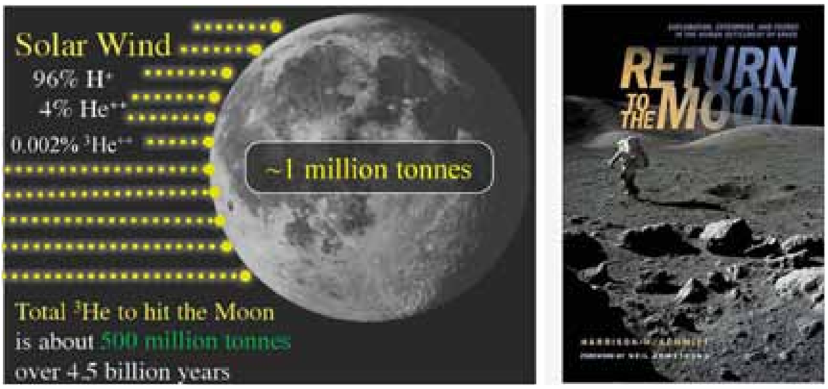
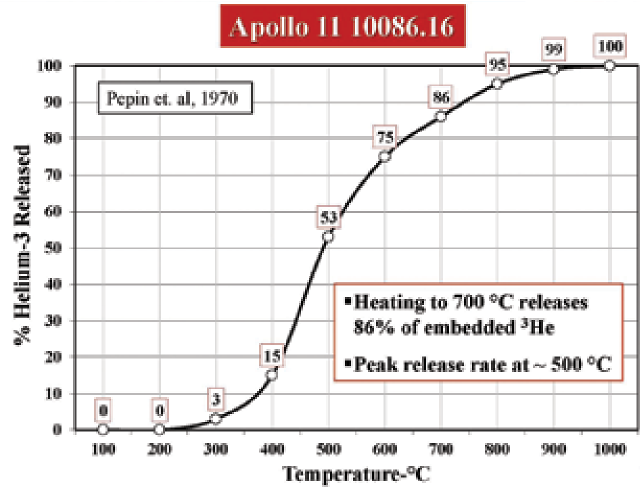
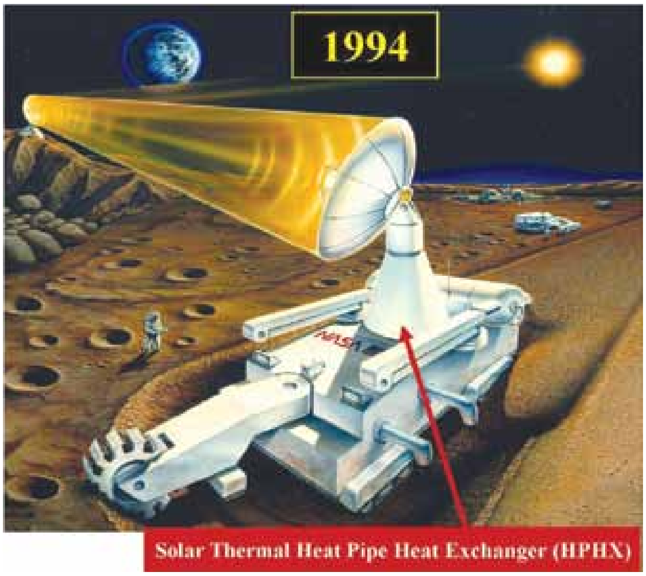


FIGURE 4

Lunar ^{3}He Miner Designs Have been Based on Recuperative Heating





Mark II Helium Mining Robot

and it really summarizes a lot of the research that had been done in the 1980s, 1990s, and even into the 2000s around this topic.

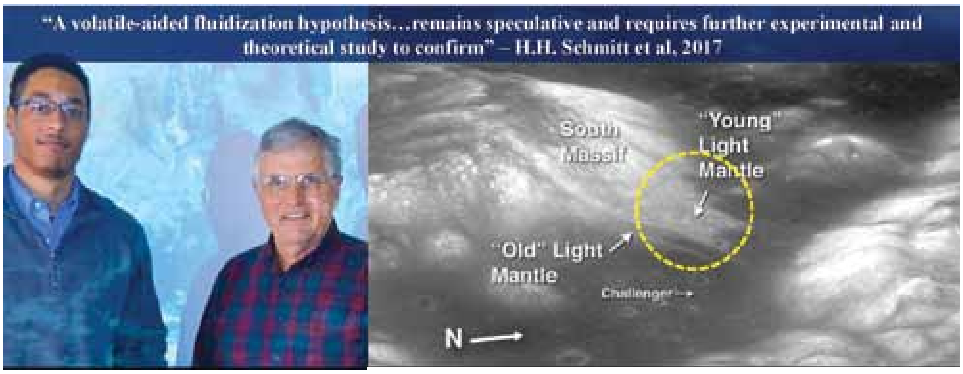
Mining Helium-3 on the Moon

As I mentioned, helium-3 can be brought out of the lunar soil by heating. We found out by tests at the University of Minnesota and the Johnson Space Center, that when lunar soil, or lunar regolith, if you will—the disaggregate that is covering most of the surface—when it's heated up to 700 degrees Celsius, about 85% of the embedded helium-3 is released.

Based on of that fact, a number of different robotic mining system designs were developed that can be used to extract helium-3 from the lunar surface. It started in the late 1980s. One of designs—the Mark II—is shown in **Figure 4**. The artwork is by John Andrews, and the lead mechanical engineer at the time who developed this was Igor Sviatoslavsky.

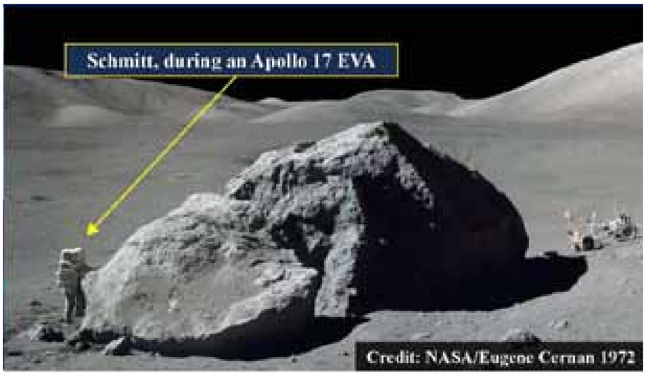
The key part of this design, the part that actually takes the soil and allows for the helium-3 to be extracted, is a heat exchanger. The heat exchanger takes energy through a bank of heat pipes from a solar ther-

It Is Believed that Agitation of Regolith Also Releases ^{3}He



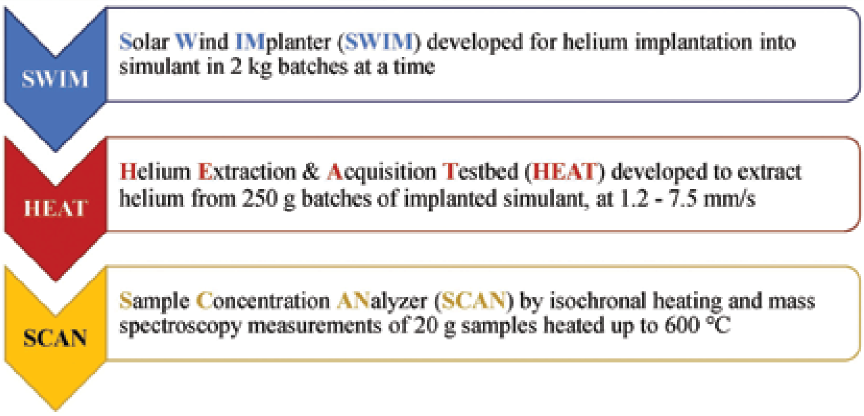
NASA LROC Image; Schmitt et al., 2017

Aaron Olson (left) and Harrison Schmitt (right), 2013.



"Losses of helium-3 from Apollo 11 fines due to agitation may be at least 42% of the concentration in undisturbed regolith"
—H.H. Schmitt, Return to the Moon, *p.92.*

Approach Consists of Three Experimental Steps



Solar Wind IMplanter (SWIM) developed for helium implantation into simulant in 2 kg batches at a time

Helium Extraction & Acquisition Testbed (HEAT) developed to extract helium from 250 g batches of implanted simulant, at 1.2 - 7.5 mm/s

Sample Concentration ANalyzer (SCAN) by isochronal heating and mass spectroscopy measurements of 20 g samples heated up to 600 °C

mal collector. Those heat pipes are what the regolith flows around as it passes through the device, heating it up and therefore allowing the gas to be released.

From his experience on the surface of the Moon, Dr. Harrison Schmitt thought that there might be another way that this gas could be released. By looking at the samples that came back from other Apollo missions and also from his own mission, Apollo 17, in 1972, he thought that agitation may also be a mechanism to release not only helium-3, but any volatile gases to be released from lunar soil.

Dr. Schmitt thought this because when he was on the Moon, he saw the trace of an avalanche, an ancient avalanche on the Moon, a flow that had travelled too far from the base of where the material started from. He thought that it must have been levitated or lubricated in some way to flow even further away from the initial mountain, if you will, on the Moon. So, he said, what could do that? There's no water, there's no liquid water on the surface of the Moon. What else could have made this material move so much farther? He thought maybe it was the gases that were released from the soil itself as it started to roll away from the base of the mountain. He said that therefore, the concentrations of helium and other gases that were coming off of the lunar samples had probably lost quite a bit not only from its handling on the Moon, but also in its handling back on Earth as it was being used for experimentation and so forth.

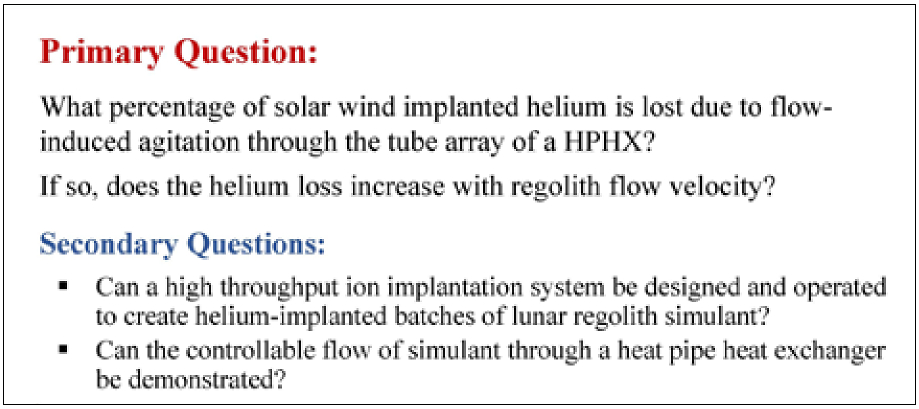
In his book, Dr. Schmitt said he believes that at least 42% of the concentration of volatile gases was removed from a lot of the samples that came back to Earth, which could be substantial. Meaning that if that much is coming off of these samples, maybe you don't need heating at all, as in some of the other robotic designs we've had before. Or maybe some combination of heating and agitation might be the right approach.

Two Approaches: Heating and Agitation

My research had two primary questions. Basically we wanted to create technology in the lab that would allow us to see how much we could get out by heating and how much could we get out by agitation; and how does the flow-rate of material through our device influence the amount that we're able to extract? I developed three sets of experiments to be able to do this.

The idea was, first we needed a batch of lunar regolith simulant that had a known quantity of helium already in it. We wanted to use helium-3 for our experiments, but helium-3 costs about $30 million per kilogram on Earth right now. As you may or may not know, most of the helium-3 that we have access to for research across the Earth comes from the degradation of tritium that's in the [nuclear] warheads. So, the United States has quite a bit of it, and Russia also has quite a bit of it. And researchers around the world, when they want helium-3, that's where they buy the material. We weren't a super-wealthy institute at the University of Wisconsin, though we do have some good resources, so as a surrogate for helium-3 we used helium-4; which

Research Objectives



Primary Question:

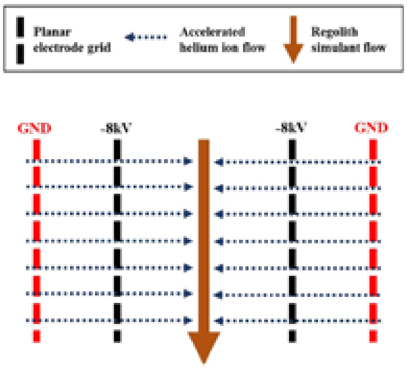
What percentage of solar wind implanted helium is lost due to flow-induced agitation through the tube array of a HPHX?

If so, does the helium loss increase with regolith flow velocity?

Secondary Questions:

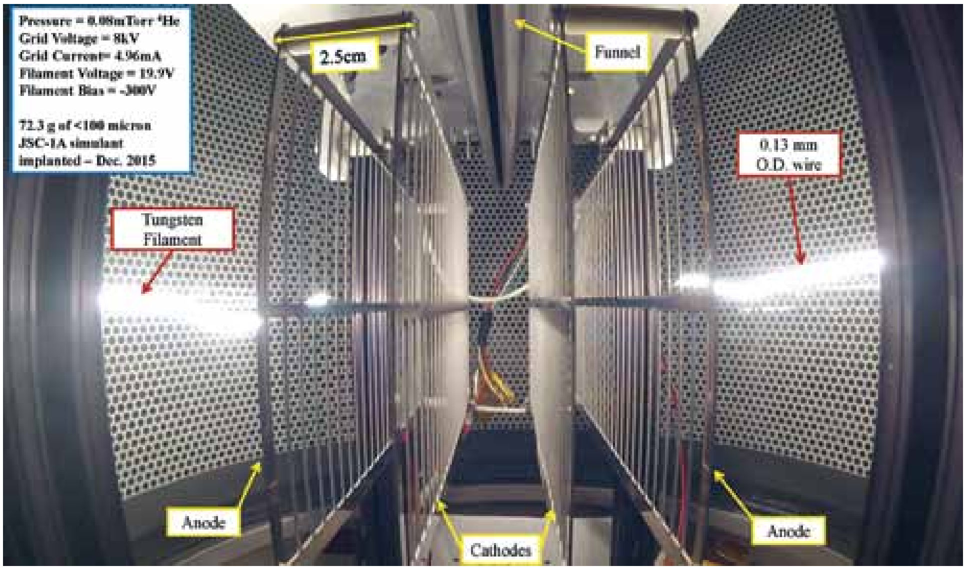
- Can a high throughput ion implantation system be designed and operated to create helium-implanted batches of lunar regolith simulant?
- Can the controllable flow of simulant through a heat pipe heat exchanger be demonstrated?

The Solar Wind Implanter (SWIM) Concept



- Implant helium into falling <100 µm JSC-1A lunar simulant
- Replicate solar wind implantation energy at ~1 keV/amu with the use of parallel electrode grids
- Use ^{4}He instead of ^{3}He due to cost and availability
  - ^{4}He diffuses out of regolith like ^{3}He

FIGURE 5



diffuses out of lunar soil very similarly, so for our cases it was basically the same.

We developed a device to implant helium into the lunar soil. We then developed a device to be able to process that implanted lunar soil in a form of a heat-pipe heat exchanger. It could raise the temperature of the regolith, and the additional elements of the heat exchanger allowed us to recoup some of that thermal energy so we wouldn't have to use so much of it to be able to raise the temperature of the regolith. Then lastly, we had a device in which we would heat up small samples of the material after it flowed through the heat exchanger, to be able to see how much remaining helium was there, therefore testing the efficiency of the device.

Implanting Helium into Regolith

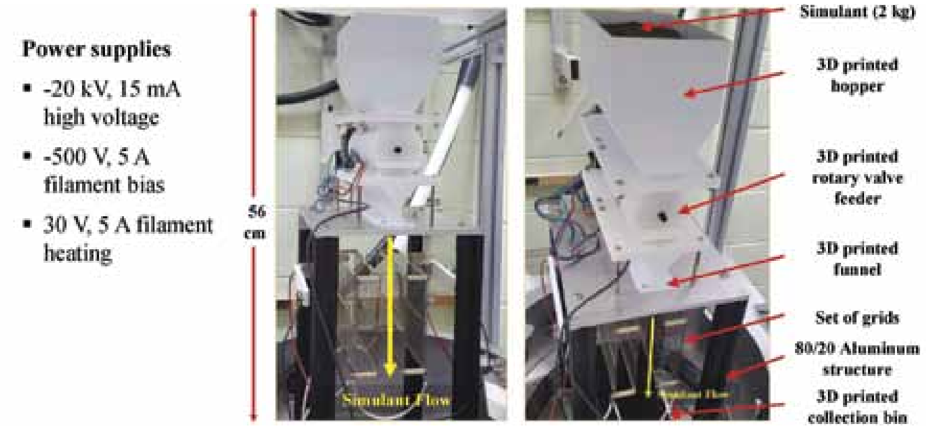
The concept around the implantation device was one that was fairly simple. We used pairs of electrodes where the cathodes would be held at a large negative voltage, and the outside grids would be held at ground. For those of you who know a little bit about electrostatics, basically that means that anything that's positively charged that's near the outside of those grounded anodes would be accelerated directly inward toward a falling stream of material. So we had a feeder device that would drop a thin stream of regolith downward, and then those two outside grids would accelerate the helium to smack into those particles and be embedded. In **Figure 5** you can see the device inside a vacuum chamber.

These outside grids here are the anodes—the cathodes obviously are in the inside, between them there—we used filaments to create some of the background ionization. We had this vacuum chamber and we filled it up with helium-4. We needed to create some positively-charged helium ions to start with, so the tungsten filaments, the same filaments that are in traditional incandescent bulbs, when they're heated up, they kick out electrons. And when those electrons smack into neutral atoms, they create positively-charged ions. So, we had this soup, if you will, of this positively-charged helium-4, and as soon as it got close enough to these grids, it got accelerated to the point that it would then embed itself in the falling material that was between the two grids.

The feeder equipment is shown in **Figure 6**. Everything that we used from the top part of this, except for

FIGURE 6

SWIM Design: Principal Components

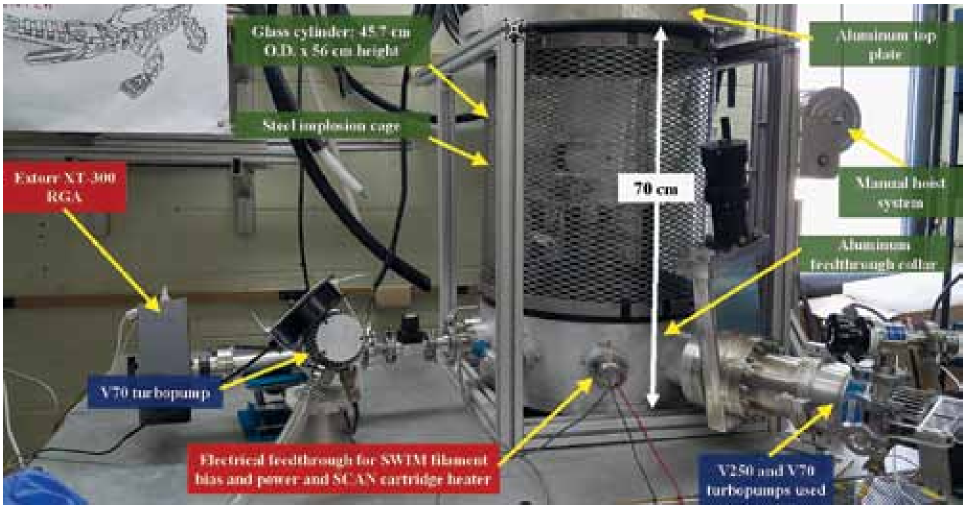


the motors and grids and so forth, was 3D printed. So, that made it a lot easier for us to be able to build something for this under a tight budget.

Processing Regolith

We learned a lot about how to process regolith. Regolith is a very nasty substance to work with. The reason is that, not only the real lunar regolith, but also the simulated lunar regolith that we work with here on Earth, is very jagged; so it sticks on everything. It's very fine-grained, so you have to wear masks when you're working around it, and whenever you touch it, it ends up sticking on your gloves and whatever equipment you're using. The feeder devices that we had to develop to be able to process it went through a lot of iterations before we got to something that actually worked reliably.

FIGURE 7



A vacuum chamber system was assembled specifically for the SWIM system.

The vacuum system that we used to do this research in shown in **Figure 7**. In the back left corner of this image, you see a part of a flag from NASA Swamp Works. I'd like to give a shout-out to their group. They provided a lot of design assistance and a lot of advising along the way throughout this project as a part of the Space Technology Fellowship Program. In particular, Dr. James Mantovani and all of the great engineers down there at NASA Kennedy Swamp Works.

FIGURE 8

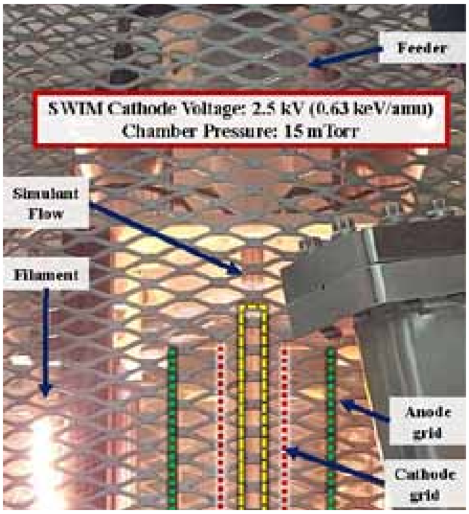


FIGURE 9

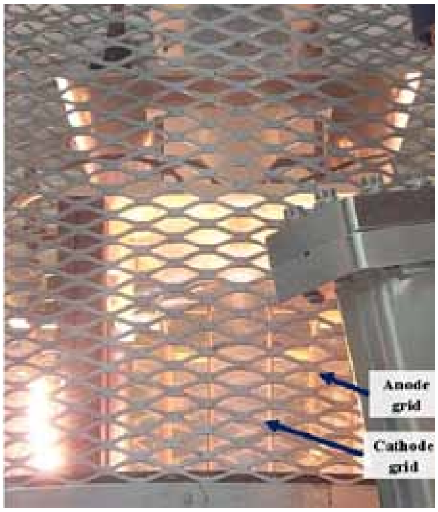


Figure 8 shows you the system in use. See the grate in front of the image? That's the protective implosion cage around the vacuum chamber. **Figure 9** shows you the falling

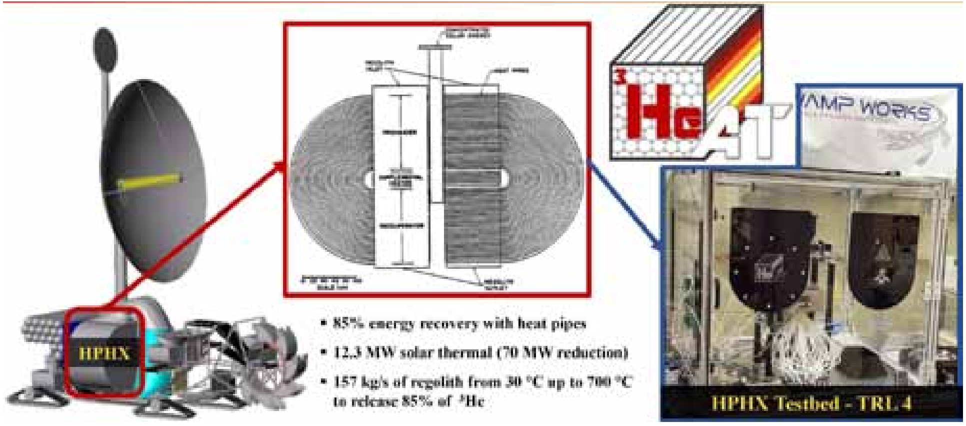
stream of regolith, which is highlighted here. You might be able to pick up a slight faint purplish glow inside of the vacuum chamber. That is the emission of light that occurs when you have these charged particles that are accelerated.

Now to the other portion of what we called the Helium Extraction Test Bed, namely the extraction or heat exchanger portion of the research. In large-scale devices, massive systems were designed, about three meters tall and about five meters in width—a gigantic device was conceptualized for this. But we needed to do something that would work in our lab in the university, so we built something that was about three feet by three feet by three feet. The glove box that it operated in can be seen in **Figure 10**, in the corner.

Similarly to the implantation device, there was a series of mechanical devices to feed regolith through the device, and on top of that there were heat pipes that were nestled in the key part of this where you see HPHX in the image on the far right. Additionally, there were a number of different spots for instrumentation where we would record temperatures, and we also passed coolant through the device in certain pieces to make sure none of the hot elements would melt any of the 3D plastic pieces.

FIGURE 10

Helium Extraction & Acquisition Testbed (HEAT) Concept



- 85% energy recovery with heat pipes
- 12.3 MW solar thermal (70 MW reduction)
- 157 kg/s of regolith from 30 °C up to 700 °C to release 85% of ^{3}He

HEAT Was Designed to Test Agitation and Thermal Extraction

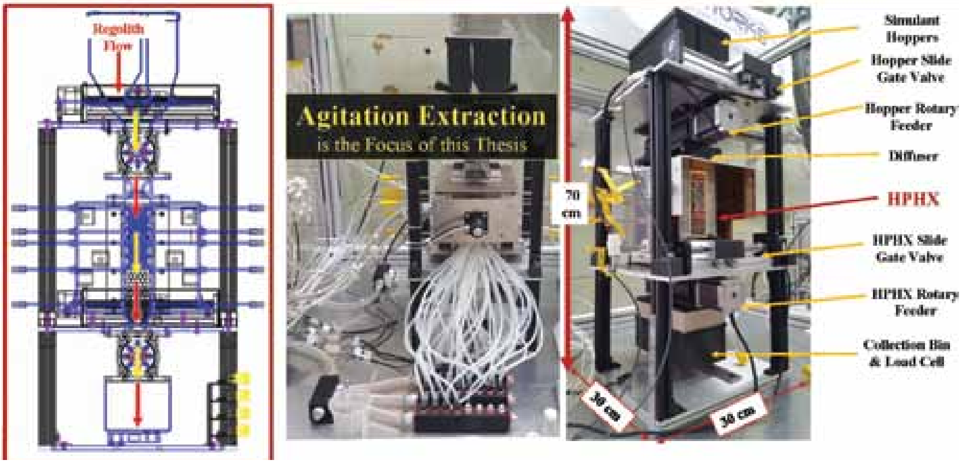


FIGURE 11

Sample Concentration Analyzer (SCAN) Components

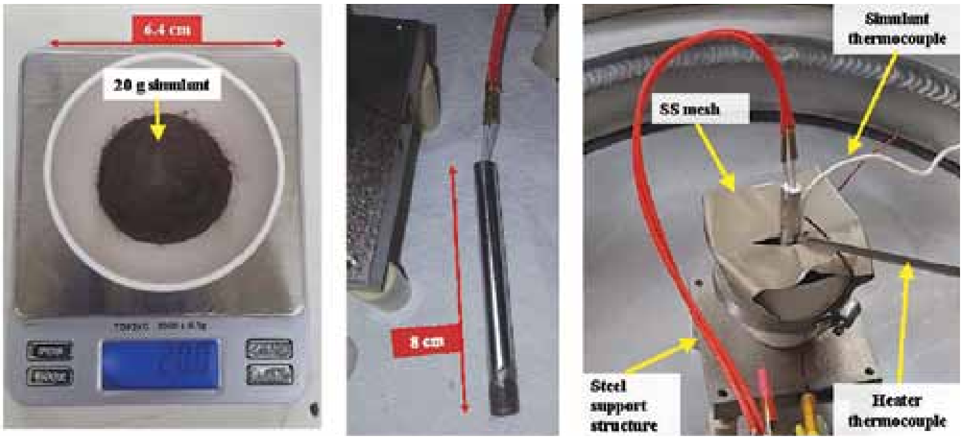
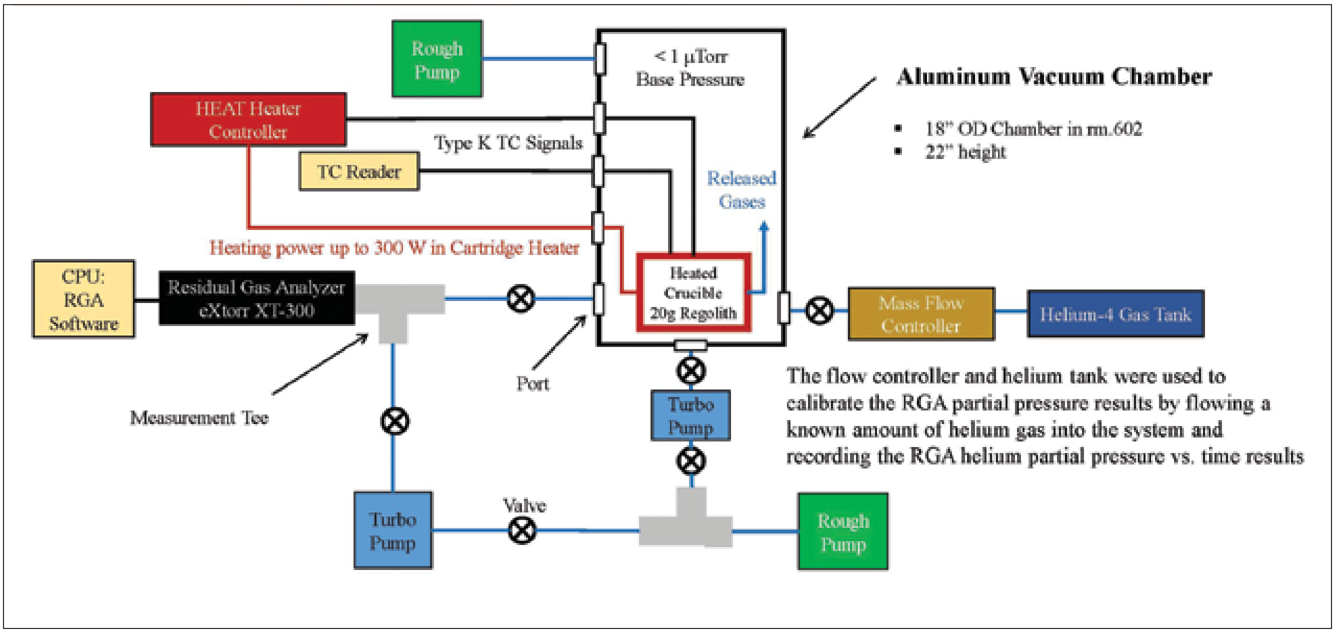


FIGURE 12

SCAN Vacuum System Setup



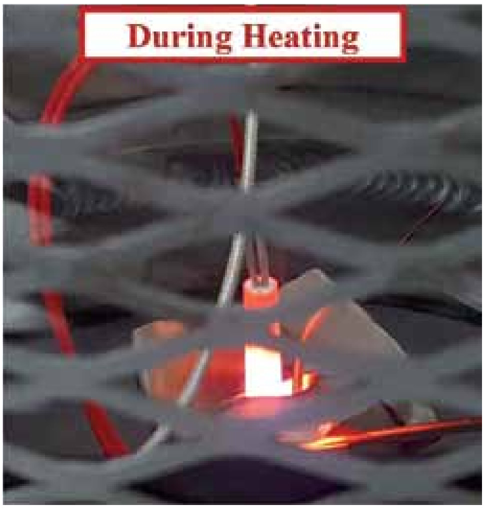
The flow controller and helium tank were used to calibrate the RGA partial pressure results by flowing a known amount of helium gas into the system and recording the RGA helium partial pressure vs. time results

Analyzing Results of Regolith Processing

Lastly, let's look at the SCAN, or sample concentration analyzer components shown in **Figure 11**. After passing a number of different series of samples through the heat exchanger, we then had to test how much helium was remaining. This is the process we ended up using, where we used a crucible. We would test about 20 grams of processed simulant at a time. We did the heating by using a cartridge heater. You might be aware of cartridge heaters for different applications in industry, but effectively it's a rod that gets extremely hot. We used ours to get to about 600-650 degrees Celsius. Then we would record the gases that were coming off of the 20 grams of simulant using a residual gas analyzer inside of a vacuum system. Here's a schematic of that vacuum equipment in **Figure 12**. In **Figure 13**, you can see an image of one of the cartridge heaters glowing hot during one of the tests.

FIGURE 13

SCAN Procedure



What We Learned

What we learned from all of this experimentation is that the simulated regolith with helium that we produced released helium in a very similar way to real lunar samples. In fact, the graph in **Figure 14** shows you a comparison of the way that helium is released as a function of temperature for real lunar samples, with other analog samples that were developed at my university back in the 1990s, and with the JSC1A simulant that I used after implantation. So, you can see the evolution curve is very similar. This gives us confidence that the work we were doing has application on a real lunar soil as well.

Figure 15 shows probably the most important conclusion of the research we accomplished. As Dr. Harrison Schmitt thought back in the 1970s, after his mission to the Moon, agitation does play a big part. There are some questions as to how deep the implantation was with our particular work, exactly how much agitation

FIGURE 14

Helium Release from SWIM Implanted Simulant is Similar to Lunar Regolith

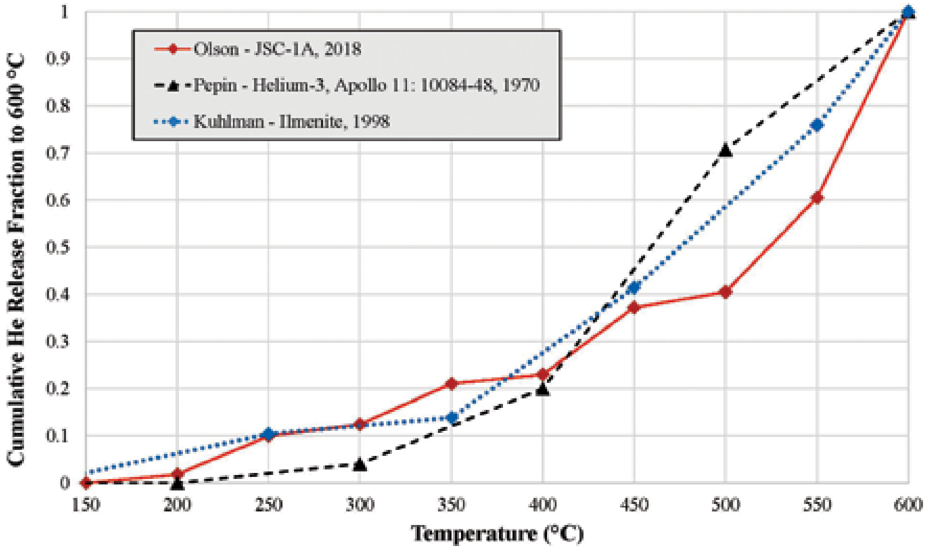
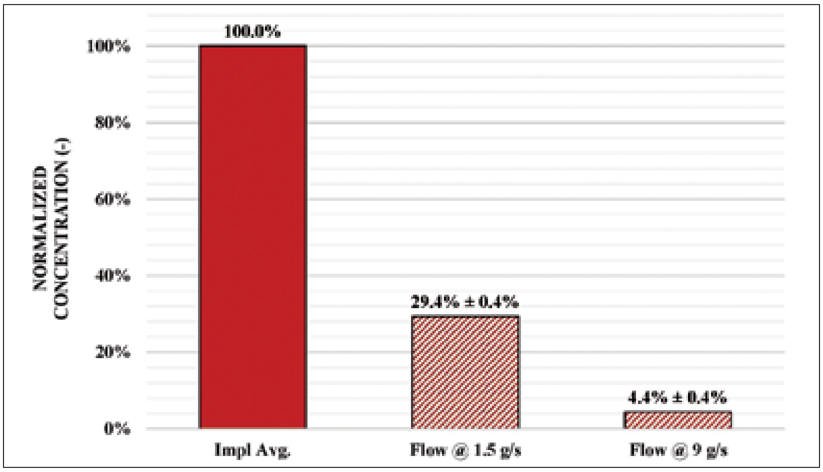
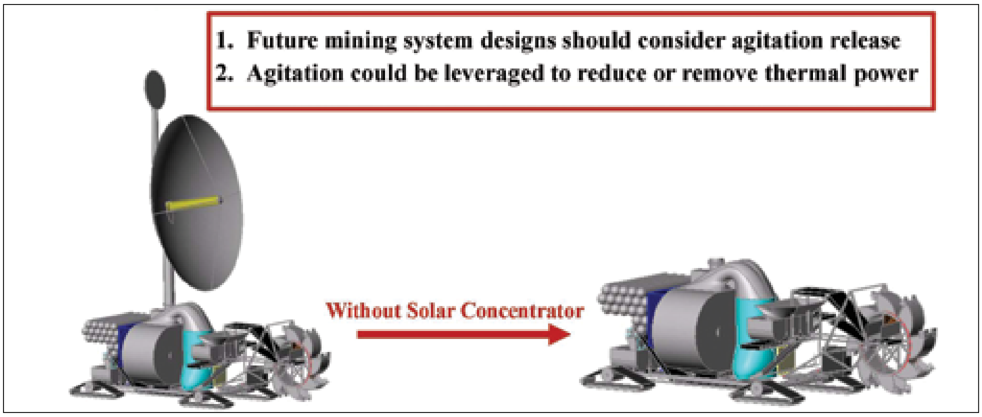


FIGURE 15

Flow Induced Agitation Reduces Retained Helium in Simulant



Agitation Substantially Impacts Helium Release in Miner Systems


1. Future mining system designs should consider agitation release
2. Agitation could be leveraged to reduce or remove thermal power

was happening with our equipment, and so forth, which is too detailed for this presentation.

But the most important result of our work, was that we recorded substantial amounts of helium being removed from our samples strictly by agitation. The agitation in our case was the movement of the material through the device. You can see in Figure 16, in the case of material flowing at 1.5 grams per second, the remaining concentration was a little bit less than 30%. That means that 70% of the helium that was implanted disappeared simply by the grains rubbing up against themselves and other pieces of the equipment as it flowed through the device. At faster speeds, more than 95% of the implanted helium disappeared.

So what does that tell us? It tells us that future mining system designs, to be able to collect not only helium-3 but other volatile gases from the lunar soil, should definitely incorporate agitation mechanisms, potentially in place of, or at least in combination with heating mechanisms.

Again, I'd like to give a big shout-out to NASA's Space Technology Fellowship program, all of the engineers and support staff over at Kennedy Space Center and at the University of Wisconsin, and in particular to Dr. James Mantovani for his mentoring throughout the process. And of course, my own advisor, Dr. Gerald Kulcinski, the leader of the Fusion Technology Institute. And lastly, Dr. Harrison Schmitt, for his motivation in the project, and for actually being on the Moon to observe some of this way back in 1972.