Questions For the Record for Dr. Moses P. Milazzo
Hearing on The Mineral Supply Chain and the New Space Race
Before the
Committee on Natural Resources
Subcommittee on Oversight and Investigations
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1. Does China have mining aspirations on the Moon?

   I believe so, but I am not a foreign policy expert. The stated goals of the Chinese National Space Administration include in-situ resource utilization (ISRU), which could be considered a precursor to mining. Several capabilities demonstrated by Chinese missions indicate they are hoping to establish a more permanent presence on the Moon. For example, the Chang'e 4 mission included plant seeds that were reported to have sprouted. Due to very low temperatures and a failure to keep the seeds warm, the experiment was terminated in 9 days instead of the planned 100. However, the experiment was successful in the sense that it demonstrated it is possible for seeds to sprout within a closed system on the Moon. On the other hand, this experiment may have been simple science similar to NASA and the US Forest Service's collaboration to bring hundreds of tree seeds from five species to lunar orbit on Apollo 14 and return them back to Earth. Despite the seeds being exposed to vacuum, they were successfully germinated on Earth.

   Despite such possible aspirations, the reality of space exploration and exploitation are very different and sending a pot of soil with seeds to space is a very early first-step. Remember, we have private companies that promised to land a rocket on Mars by 2016 (and 2018 and 2020 and…). Space exploration for science is very difficult, but space exploration for resource extraction is exponentially more difficult and does not yet provide returns on investment. Many entities have aspirations of mining on the Moon or asteroids but the reality is that there are significant hurdles to achieving those goals.

2. How far along is China in advancing space mining?

   China is far from space mining. To date, China has returned a sample of the Moon back to Earth with its Chang'e 5 lunar sample-return mission in 2020. This sample had a mass of 1.7 kg. By comparison, the US has a total of 382 kg of lunar materials that were returned from the Moon with the Apollo missions; however, these samples would not be considered “mining.” True mining requires significant and rarely-discussed technological advancements.

3. How accessible are critical minerals on the Moon?

The talk of untold riches in space is similar to the story of El Dorado, the legendary and mythical city of gold that led many explorers astray. In one sense, critical minerals are all over the Moon–there are *small* amounts in nearly every scoop of lunar regolith (soil). However, these critical minerals are not realistically accessible and critical minerals that are most abundant on the Moon are already easily accessible on Earth. Specifically, minerals that are abundant on Earth, for example, plagioclase, pyroxene, olivine, and ilmenite, are also abundant on the Moon and on many asteroids. The metals associated with these minerals include Calcium, Aluminum, Silicon, Iron, and Magnesium. However, these are also highly abundant on Earth and the relative costs to acquire these minerals on Earth instead of in space are many orders of magnitude lower. Less common minerals and metals (such as Rare Earth Elements or REEs) are, in many cases, only available on the Moon and on asteroids in concentrations of parts per billion (ppb), meaning one would have to process a billion kilograms of material, at 100% efficiency, to obtain a single kg of pure mineral or metal.

Mineral maps of REEs on the Moon and asteroids may appear to show rich resources available at the surface, but this is only because the maps are intended to show differences in mineral concentrations; what appears to be a dramatic difference on the map may only be the difference between 2 ppb and 0.5 ppb. At this point in time it is not economically viable to process billions of kgs of material for the reward of only a few kg of minerals on the Earth, much less in space.

While we might consider infrastructure materials (steel, aluminum, etc) to be especially important to a space race that includes mining and other infrastructure developments; we need to also keep in mind other critical components of the infrastructure. For example, carbon is essential in producing steel from iron but is only seen in concentrations of less than about 100 ppb on the Moon. Carbon steel typically has a carbon content of 0.05% to 2.1% by weight. Accordingly, to make a metric tonne (1000 kg) of steel, we would need to gather between 0.5 and 21 kg of carbon. If one plans to mine all of their resources in space, that would require processing between 5 *million* and 210 *million* kg of material on the Moon to obtain the necessary 0.5 to 21 kg of carbon for producing 1 metric tonne of carbon steel. To develop a realistic mining infrastructure on the Moon, we might need several million metric tonnes of steel. In other words, we might need to process up to 100 trillion kg of material to build the infrastructure if we only use material acquired in space. A rough estimate for the average mass of near-Earth asteroids is around a trillion kg. While some of the near-Earth asteroids will probably have higher carbon concentrations than others, the reality is that a mining operation intending to acquire carbon and iron for creating infrastructure components might need to process an entire asteroid, or, more likely, several.

Carbon is just one of the many “minor” infrastructure components required to see realistic returns on mining in space that either needs to be acquired from somewhere in space or launched off the Earth. Neither option would be cheap or easy.

In addition, to acquire and process these millions to billions to trillions of kg of materials on the Moon, we would need very large transportation networks (many hundreds to thousands of km of trains, for example) to move these materials from their source to their refining centers, and those networks will depend on battery and solar power technologies as well as many materials acquired from the Earth and launched into space. If we were to build the networks for mining on asteroids and bringing materials back to Earth or to the Moon, we would also need a similar “train” of rockets to transport those materials.

The infrastructure requirements to expand humanity from Earth to anywhere beyond low Earth orbit are tremendous and incredibly complex, meaning any such effort will be expensive.

4. What are lunar “mascons”?

Mascons are positive gravity anomalies relative to the mean shape of the body. For the Moon, this usually means there is a depression of some kind that has a higher gravitational pull than would be expected if mass were missing from this area. These are almost always in areas where there were large basaltic lava flows called “mare basalts”. These “mare basalts” are similar to Hawaiian basalts and consist mostly of pyroxene, plagioclase, and olivine, with minor amounts of other minerals. While there might be small amounts of critical minerals in some basaltic deposits on Earth or on the Moon, the concentrations are such that it’s simply not economically sensible to go after these sources of minerals because on Earth, hydrothermal systems have, over eons, concentrated these minerals for us for free. If these deposits had valuable concentrations of critical minerals, we would see terrestrial mining companies processing basaltic lava flows on Earth. Hydrothermal systems are not known to have occurred on the Moon or asteroids.

Related to mascons, there is a common misunderstanding regarding the formation of impact craters that an impacting object remains at the bottom of the resulting crater. However, most or all of the impacting object is vaporized and material is spread all around the impacted body, first as vapor that may be put into orbit (or may be pulled down to the surface of the body), which cools, condenses, and eventually joins the rest of the regolith on the surface. This wide dispersion of the vaporized material means that the concentrations of whatever material made up that impacting object are extremely low. This critical misunderstanding cost an Earth-based speculator in Arizona his entire fortune. Daniel Moreau Barringer staked a mining claim at what is now known as Meteor Crater in Northern Arizona, believing that a 50-meter diameter nickel-iron asteroid, with a mass estimated (by Barringer) to be 100 million tons (or worth around $1B in 1903 dollars) had formed the crater and was buried beneath the surface. In actuality, the impactor had vaporized upon impact and had rained out over a wide area. Pieces of this meteoroid can still be found in the surrounding area. Barringer's work to find this imagined fortune greatly improved our understanding of impact crater events, but it did nothing to make him rich.

5. What is Helium-3 (He-3)? What are its uses and how accessible is it on the Moon?

He-3 is an isotope of Helium that can theoretically be used as a relatively clean fuel for fusion. However, this is currently a science-fiction fantasy. We have no human-built operational fusion reactors other than nuclear bombs (which do not use He-3). The only other known, operating fusion reactor in our solar system is the Sun. Theoretically, fusion reactors may someday be usable, and our national laboratories may be on the verge of sustained nuclear fusion ignition in a laboratory setting. But, for nearly a century, we have speculated that we are "just" 30 years away from a solution for fusion power using known fusion fuels like deuterium (D) and tritium (T). We have never worked out a technological method for using He-3 in a fusion reactor because it is far more difficult than D-T or D-D reactions.[1]

Not only is the use of He-3 still far-future science fiction, its concentrations are, at best, only in the parts per billion on the lunar

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[1] https://www.thespacereview.com/article/2834/1

surface, so even if we could figure out how make He-3 fusion work, we would have to mine billions of kg of material to get a single kg of He-3. Moreover, containing and keeping He-3 pure and usable as a fuel is a non-trivial challenge.

He-3 is a potential clean fusion source for far-future use, but is not a practical goal in near-future commercial exploitation of space and is probably a direct road to bankruptcy because of the significant study still needed in physical laboratories before it could be ready for use in Earth reactors, much less space-based ones.

6. Some private companies are exploring methods for processing minerals in space. How close are we to successfully mining celestial objects and processing the resulting materials for use on Earth?

We are in the early stages of forming theoretical methods for processing minerals in space but are still decades away from successful mining of celestial objects.

One company tried to put into practice a theoretical method that imitates gravitation separation for processing mineral ore in low earth orbit, but encountered multiple problems with its first experiment. Gravitational separation is the least energy intensive method we have for processing mineral ore on Earth and essentially uses the fact that minerals all have different densities to separate them from each other. On Earth, we can shake, agitate, or otherwise disturb a mixture of useful minerals and less useful materials to separate them according to their densities. A good example is panning for gold: we put some soil that might contain gold into a pan of water and agitate it for a bit. The water allows the less dense materials to float when agitated while the more dense gold sinks. We remove those less dense materials and are left with a more gold-rich soil. We can repeat the process to further concentrate the gold in the soil. This process is similar to the industrial processes used to separate large volumes and masses of minerals from their ores.

There are several theoretical ways to imitate gravitational separation for mineral processing in space, one of which is to use magnetic fields to create the separation. This method uses the magnetic properties of minerals rather than their densities to create separation and is the method the space mining startup attempted. However, testing the theory became impossible because of numerous spacecraft issues directly conflicted with testing requirements. Specifically, large magnetic fields generated on low-earth orbiting spacecraft interfere with the spacecrafts' attitude and control systems and cause the spacecraft to tumble out of control. The strength of the gravitational field required for differential mineral processing is so large that it would be nearly impossible to cheaply shield the spacecraft's attitude control system from that magnetic field. The energy costs to scale this magnetic field to process more than a few grams at a time become astronomical.

Outside of Earth's orbit, gravitational separation could be simulated in spacecraft under constant rocket acceleration that generate the needed simulated gravity, but this is incredibly expensive and would require a long time and a corresponding amount of fuel for the separation to occur.

A centrifuge could be used to simulate gravity but again, for large masses (in most cases billions of kg of material processed to obtain a single kg of usable mineral), this becomes extremely expensive. We might try to do this on the Moon, but the lunar gravitational field is one sixth the strength of Earth's, so the time needed for processing would be greatly increased and would require greater energy expenditures. And, as noted previously, all of this is theoretical and untested in any capacity.

7. How could the circular economy on Earth be useful for acquiring critical minerals?

Earth currently produces about 50 million tons of electronic waste every year. In addition, we also generate huge amounts of unmonitored non-electronics waste that contains critical minerals and metals. Our landfills are overflowing with decades' worth of electronic and electrical waste that hold critical metals and minerals in concentrations thousands of times greater than our most productive mines. There currently exists a secondary market of individuals who buy old CPUs on popular auction websites to process and collect the gold from those CPUs; even at very small scales, this is lucrative. At scale, processing landfill and recycled materials for critical minerals is probably the most lucrative approach to filling the gap in our critical minerals needs; companies looking to seriously produce low-cost precious metals and critical minerals would be wise to start with landfills.

8. Should the United States be concerned about its future access to space, the Moon, or the rest of the Solar System considering claims that foreign adversaries are investing in settlements and mining projects in space?

I don't believe so. Our access to space is limited only by our ability access near-Earth airspace; once a rocket moves away from Earth and into space, its access to the Moon, asteroids, and the rest of space increases with its distance from Earth. If a foreign adversary wanted to threaten our access to space, it would have to do so as near to the Earth's surface as possible, which raises a far different issue. Once an entity begins operations in space, the danger posed by any kind of adversary significantly diminishes.

While international space agreements could be improved and updated, the reality is that once an entity has established a safe way into space, its access to space is unlikely to be threatened by the presence of another entity.

That's not to say foreign adversaries building access to space is without potential danger. Most significantly, there are cultural treasures in space, both human-made and natural, that may be threatened by entities disregarding existing or future international agreements. I believe a diplomatic approach, both within the United States and internationally, is most likely to result in successful protection of cultural artifacts, environmental conditions, human rights and lives, and technological advancement.

The most consequential limitation on our ability to access space will not come from foreign adversaries, but from our own willingness to fund education and the necessary research for advancement in energy resources. We are woefully behind other nations on crucial technologies such as large capacity battery storage and solar power generation and are expending pointless time and energy fighting ourselves over those technologies and the ones they will need to replace (fossil fuels will be useless in space). We have lost the edge on education; our national fear of innovations in science, mathematics, and humanities education has put us decades or more behind the technological advancements of other countries. We fight our own workers and labor unions instead of incentivizing them to be innovative and productive. If we want to lead in space, we must return to our position as a global leader in education, workers' rights, and human rights in general.

9. Besides on Earth, is there currently any permanent human presence in the solar system?

   No. The closest anyone has to a permanent human presence in the solar system is the International Space Station. We have robotic space missions exploring the solar system, but the farthest humans have gone outside of low Earth orbit is to the Moon. Eugene Cernan commanded Apollo 17 (11 to 14 December, 1972) and was the last person to walk on the Moon. The crew of Apollo 17 were the last humans to travel outside of Earth's orbit.