An Overview of Lunar Resources for Mining and Extraction

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With NASA's Artemis program taking humans back to the Moon, it draws the question: Why go? The Artemis program will take us to explore and further our knowledge of science. However, without a clearer return on investment, establishing a long-term presence on the Moon will not be a sustainable future. Eventually, as with the Apollo program, the public taxpayers will become disinterested in paying for a few people to step foot on the lunar surface. Unfortunately, this view stems from a misunderstanding of the Moon's long-term resources. The United States, whether through private industry or government projects, must look to the prospect of taking advantage of the plentiful and accessible resources available on the Moon. Without mining, going to the Moon and building a base along with other infrastructure will be far too expensive to justify in the long term. There are two phases to lunar mining. The first is in situ resource utilization (ISRU), which will be used to build the infrastructure needed for a base, mining camp, and exploration. The second will be materials that are extracted and shipped here to Earth. For phase one, water will likely be the most valuable commodity found on the Moon. Water exists in the form of ice in the lunar south pole, which can be extracted, melted, and purified for drinking water, hygiene, and hydroponics. Additionally, Hydrogen could be extracted for rocket fuel. The second phase of mining operations would come after the base has sufficient resources to aid itself in sustainability. Helium-3 (^{3}He), which could be used for nuclear fusion, is on the surface. This could be mined by processing lunar regolith by heating it to release the ^{3}He. Nuclear fusion is a possible contender to provide the United States with an abundant energy supply that is highly efficient, clean, and safe, making ^{3}He a very valuable raw material. Many other rare earth metals on the Moon can be capitalized on to justify the cost of going. These can be utilized or sold to invest in future exploration. This research paper will narrate the mining options a lunar colony can employ to sustain itself and offset the cost of sending crews and supplies to the Moon.

I. Nomenclature

C = degrees in Celsius
GW = gigawatt
kg = kilogram
km = kilometer
L = liter
ppm = parts per million
ppb = parts per billion
ppt = parts per trillion

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II. Introduction

Return on investment is a core concept in business or any financial undertaking. For a venture to be successful, the investor needs to see more profit than what was originally invested. A viable lunar colony needs to utilize the plentiful resources available to them. Not only to build the infrastructure needed to sustain colony, but also to send back to Earth a profitable means to offset the enormous expense of getting there. A three-phase plan to colonize the moon has been drafted by using raw materials to illustrate where the goals and priorities should lie for each stage. A breakdown of the resources that would be most valuable in each phase is shown along with their uses, potential for profit, and how to mine or extract them.

III. Phase One: Building a Colony

A. In-Situ Resource Utilization

In-situ Resource Utilization is the practice of using natural materials found at the destination to build, grow, and create anything needed, rather than bringing everything required with the crew. This idea makes going to the moon considerably cheaper and more efficient. It costs around $1.2 Million to put one kilogram of supplies onto the lunar surface [1]. At that price, it is not practical to send everything needed, but to only send what is necessary to get started. A good example of this is common metals found in the lunar regolith. It would be far cheaper to take supplies to process raw iron or aluminum and then use what is already there, then attempt to launch the hundreds of kilograms of metal needed.

B. Oxygen

The chemical composition of regolith is made up of 99% major elements and 1% minor elements. The major elements are oxygen, silicon, aluminum, calcium, iron, magnesium, and titanium. The minor elements are manganese, sodium, potassium, and phosphorus [2]. Oxygen makes up the majority of the regolith, usually consisting of 45% of the composition. For every cubic meter of regolith, there is on average around 630 kg of oxygen. A large part of the lunar colony's operations should include mining the lunar regolith for the elements. This would be done by processing large amounts of regolith and then removing the useful elements. Oxygen has obvious benefits, mostly for filling the base and Extra-Vehicular-Activity (EVA) suits with breathable air. NASA successfully removed oxygen from a simulated regolith, proving that it is possible [3]. They achieved this by heating the soil with a carbothermal reactor, which released the oxygen particles. Oxygen is also a byproduct of the aluminum refining process. Any aluminum gathered in the regolith can be smelted down and produce aluminum for building infrastructure and oxygen for breathing or treating iron. Iron is made stronger when oxygen is directed to flow over molten iron. The oxygen produced from the aluminum could be used to treat iron.

C. Common Metals

Iron, aluminum, and titanium are all metals that are super valuable to find on the moon. 1 cubic meter of iron, aluminum, and titanium weigh 7870 kg, 2700 kg, and 4540 kg respectively. It would cost 9.4 million to ship just one cubic meter of iron to the moon. A base or any other structure needing to be built would require a lot of metal, so using metal elements already on site would be much more cost effective, albeit slightly more work. The elements will need to be separated from the other minerals and then purified of any impurities. It can then be smelted into metal panels, trusses, and bars. The astronauts could build their permanent hab out of the metal, using bars to frame the outside and welding panels around these to enclose the hab. Trusses could be used as the top and bottom of the structure to ensure a sturdy foundation. Titanium would make a good roofing panel as it has the highest density of the three materials, and the atomic structure of titanium allows it to better absorb and protect the crew from hazardous radiation.

D. Water

Water exists in the form of ice on the moon. Research suggests that ice is common in areas that receive no sunlight, called "permanently shadowed regions", which exist mostly around the lunar poles [4]. NASA's Lunar Reconnaissance Orbiter (LRO) and the Indian Space Research Organization's (ISRO) Chandrayaan-1 probe have both mapped the lunar south pole and have used radar to estimate there is 600 billion kilograms of ice. The lunar south pole shows considerably more ice than the north pole as seen in Fig. 1.

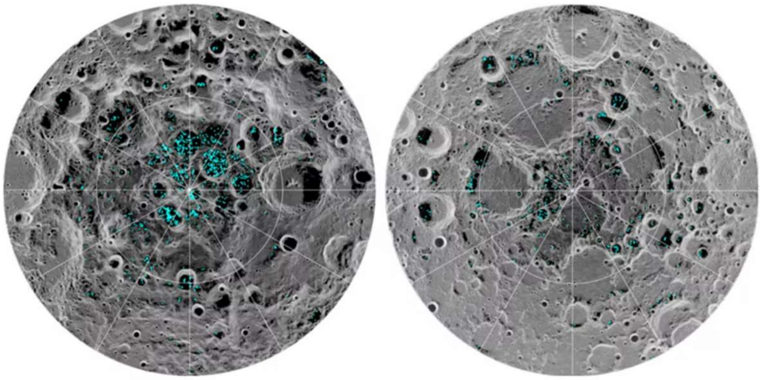

Fig. 1 NASA's Moon Mineralogy Mapper instrument abord Chandrayaan-1 shows the difference in amount and location of ice in the lunar south pole (left) and the lunar north pole (right). [4] NASA Ames Research Center

Figure 1 also shows that the location of ice primarily exists in deep craters that never see the light of the sun. A few of the most promising craters are Shackleton, Shoemaker, Cabeus, Haworth, Faustini, and Amundsen craters, which are all estimated to be abundant in water ice. Astronauts could rappel into the craters to search for ice. However, risks include the extreme cold temperatures, dark conditions, and great depth. The temperature in the bottom of the crater is estimated to be -190 °C [5]. While this makes good conditions for trapping water particles as ice, it poses challenges for protecting astronauts. These craters also have depths ranging from 4.2 km to 2.2 km deep [6]. This would be challenging to enter, but rappelling down would be a good solution. Attempting to land a lander inside the crater would be extremely dangerous because of the darkness. The pilot would not be able to see the ground beneath them and could land on uneven terrain, causing the lander to tip over or worse.

With those challenges in mind, Shackleton or Shoemaker crater would make prime spots to plant a base as they would be close to water. However, if water is so difficult to acquire, then why spend so much effort mining and extracting the ice? Water would be an invaluable resource on the moon. Water weighs 1 kg/L on Earth, and the average male should consume 3.7 liters of water daily, and the average female 2.7 liters daily to stay healthy [7]. For a crew of six astronauts (three men and three women), the crew would need 20L of water daily just for drinking. Roughly 1-2 cups of water are needed to rehydrate a personal sized meal. This would require an additional 8.5L for cooking daily. This estimates the crew will use 200L/week. For hygiene, the crew could utilize water-efficient showerheads which put out 9L/min. A very quick 2-minute shower once per week puts the crew at 108L of water for weekly hygiene. Without any other uses such as the toilet or growing hydroponics, the colony will easily need 308 liters per week. Recall that water's conversion rate is 1 kg/L, meaning that the mass of 308L is 308kg. At the current rate of $1.2 Million/kg, it will cost at least 555 million to provide the water needed to sustain a crew for one week and 13.3 billion to sustain a six-person crew for six months. For comparison, NASA's budget for the fiscal year 2023 is only 25.3 billion [8] meaning that to supply 6 astronauts with water for a year would use more than NASA's entire budget for that year. That does not include any other supplies or base infrastructure needed, just water would cost 26.6 billion.

This staggering price tag on water makes one thing clear: water cannot be brought along with the crew. To be sustainable, the colony needs to rely on ISRU by finding and using water from the craters in the south pole. Water could be brought along to get the crew set up initially, but once there, the extraction of ice should begin immediately. Reconnaissance missions should be done ahead of stationing crew members on a permanent base to determine which crater has the most and easiest to access ice. Once good ice deposits have been found, the extracted ice could be melted, purified, and used for many different purposes. It would remove the colony's dependency on earth to ship water, cutting billions of dollars in cost. This all-natural lunar water could be used for drinking water, cooking, growing plants in hydroponic stations, hygiene, and many other purposes. Additionally, water could be put through the process of electrolysis and separated into hydrogen (H) and oxygen (O).

E. Hydrogen

One challenge to going to the moon is the fuel needed to get there. Most rockets use all their fuel launching from Earth into low Earth orbit (LEO). If rockets could refuel in low lunar orbit (LLO), then this would save a lot of money and room needed to bring along extra fuel. A refueling station could be built on the lunar surface by using electrolysis on the ice water collected. The electrolysis process will separate hydrogen and oxygen. Hydrogen can be used to make cryogenic propellant by combining liquid hydrogen (LH_2) and liquid oxygen (LOX). Both are cooled down to compress them into small tanks. They need to be cooled to -253°C and -183°C respectively [9].

IV. Phase Two: Mercantilism

A. Mercantilism

Thus far, the colony has employed in-situ-resources utilization to gather supplies and use them to build the base and move towards the path of self-sufficiency. However, it is time to shift to the next phase in conquering the moon: mercantilism. This is a system where a mother country sends the initial supplies along with a group to start a colony in the new world. Upon arriving, the colony gathers raw materials and ships them back to the mother country, where they are processed and made into finished goods. The mother country then ships finished products back to the colony to be used. This mutually beneficial scenario is how America was founded and would be a good way to get a thriving lunar colony on its feet. In this case, the mother country would either be NASA, or an American private company and the colony would not be headed across the sea but rather sailing across the stars to a far away land. At this point in phase two, the lunar colony should have a self-sufficient base at the south pole. The astronauts need to make a shift from gathering resources that help them and moving towards resources that could help Earth. The moon is abundant in natural resources that are considered highly valuable on the Earth.

These resources could be mined and sold to private companies on earth or utilized by NASA to further exploration and expansion of the colony. Because going to the moon is so expensive as shown by the cost of shipping water or metal to the surface, a long-term colony will need to have a large income to offset the tremendous costs.

B. Helium-3

Helium-3 (^3He) is a stable, non-radioactive isotope of helium (He). ^3He is very light, and made up of two protons and a neutron, whereas helium contains two protons and two neutrons [10]. ^3He is expelled from the sun in solar wind and bombards the Earth and the moon with ^3He particles. However, the Earth's magnetic field deflects the helium, making it very rare on Earth. The moon, however, has no magnetic field, and has been basking in solar wind since the beginning of time. Therefore, the lunar surface is covered in ^3He. The Apollo 11 mission collected samples of regolith which showed that ^3He existed in relatively high concentrations of 13 parts per billion (ppb) but could exist in concentrations of 20-30 parts per billion (ppb) in undisturbed regolith, and triple that in the colder south pole [11, 12]. For comparison, Helium exists at a concentration of 5.2 ppm in Earth's atmosphere, and ^3He makes up about 0.0001% of all helium on Earth [13]. That amounts to a very rough estimate of 5.2 parts per trillion (ppt). To illustrate how vast this difference is, a billion grains of table salt would fill a small bathtub, but a trillion grains of salt would fill a classroom. The 20-30 ppt of ^3He on Earth would be like finding just twenty grains of salt in a classroom filled with salt. However, the 5.2ppb of ^3He on the moon would be much easier to find as there would be 20 grains of salt in a bathtub. Albeit still low concentration in the lunar soil, that is a huge number. This would mean that 100 kilograms are in the top 6 meters in a square km of lunar regolith [12].

Nuclear fusion is what makes Helium-3 so valuable. ^3He is a possible contender to provide the United States with an abundant energy supply that is highly efficient, clean, and safe. The process of gaining energy comes from combining Helium-3 with Deuterium (^2H), a stable isotope of Hydrogen. In phase one, water was the most valuable raw material, but moving into phase two, ^3He surpasses that easily. Theoretically, if 500 kg ^3He were brought back to earth and fused with ^2H at a ratio of 1:0.65, the reaction would produce 5 GW of energy, capable of powering a major city (population ≈ 3 million such as Chicago) for a full year [14]. That would only require 5 km^2 of lunar regolith to be processed. The financial worth of powering a city that large for a year is invaluable, estimated to be at least $11 billion dollars, likely more. For a private company to power several major cities, a sizable profit is sure to be found. It is impossible to know what the cost of mining 5 km^2 would be, but mines on Earth can work through that very quickly. Though mining the moon presents many more challenges than Earth, it should not take drastically longer than mining that same amount earthside.

The process of extracting the ^3He from the regolith is simple. The lunar soil needs to be collected in large amounts, possibly through the means of a bucket excavator of sorts and transferred into a heat chamber via conveyor. The material needs to be heated to 730°C for the most efficient release of helium [15]. The chamber needs to trap the released gas and bottle it into tanks. These tanks can be shipped back to Earth for use in nuclear fusion reactors. Storing the ^3He in gaseous form would be easiest as it would not need to be refrigerated for the trip back to Earth.

While this will be a heavy initial investment, the expenses of building and operation of the mining colony should breakeven within five years [16] and then start to turn very large profits.

C. Rare Earth Metals

Rare earth metals or rare earth elements (REEs) are a group of 17 metals known as lanthanides that are used heavily in the tech sector. These elements are not necessarily rare on Earth, but are only found in very small quantities, making them near impossible to mine. The most common light REEs on the moon are Lanthanum (La), Cerium (Ce), Praseodymium (Pr), Neodymium (Nd), and Samarium (Sm). The most common heavy REEs found are Scandium (Sc), Yttrium (Y), Gadolinium (Gd), Terbium (Tb), Dysprosium (Dy), and Erbium (Er) [17]. These all are highly valuable on Earth and could be beneficial in adding to the mining profit.

V. Phase Three: Continuing Exploration

A. Scientific Research

A lunar colony must employ various forms of mining for sustainability; however, it cannot get so caught up in mining that the original purpose of going is forgotten. The Apollo program focused on research and learning more about our satellite. The Artemis program has a similar focus of exploring and researching science on a moon base. Once the mining operations are running smoothly and the colony starts to turn a profit, the colony should invest in expanding the base. A larger hab to fit a larger mining crew, and scientists would be needed, along with a laboratory for scientists to begin research of the lunar south pole and its surroundings. The scientists could use rovers or landers to move farther away from the mined areas and find undisturbed regolith and craters to take samples and gather various data. NASA or the private company that owns the base could also sell seats to other companies or foreign space agencies to be stationed at the colony for a few months.

B. Looking Beyond the Lunar Horizon

Thus far, the focus has been on implementing a plan to create a self-sustaining lunar base. However, if operations run without many setbacks, then the base should be making money within a few years of beginning the venture. The company will be earning at least $11 billion in revenue per 3 million people (a major city) relying on power from the fusion reactors [14]. While the expenses of running the base and mining operations are unknown, powering just a few cities could put the company in a very wealthy position. For comparison, it is estimated that SpaceX only made 8.7 billion in revenue in 2023 [18]. With several cities, NASA or the private company would have a far larger profit than NASA or SpaceX's current budget. With this, technological advancements and innovation could advance at a faster pace, allowing exploration to be pushed further into our galaxy.

VI. Conclusion

To make returning to the moon more feasible and self-sufficient, a three-phase plan has been drawn out. Phase one is about cutting costs of the program by supplementing and then ultimately solely relying on resources already on the moon. Phase two is about making a profit to pay off the debt of phase one and provide funding for phase three, which seeks to expand the base and mining colony and then look towards future exploration ventures past the moon. While just going to the moon to explore and research would be ideal, it is not realistic. However, if the program can pay for itself, and provide for future missions, then going to the moon is sustainable and will be more likely to be successful overall.

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