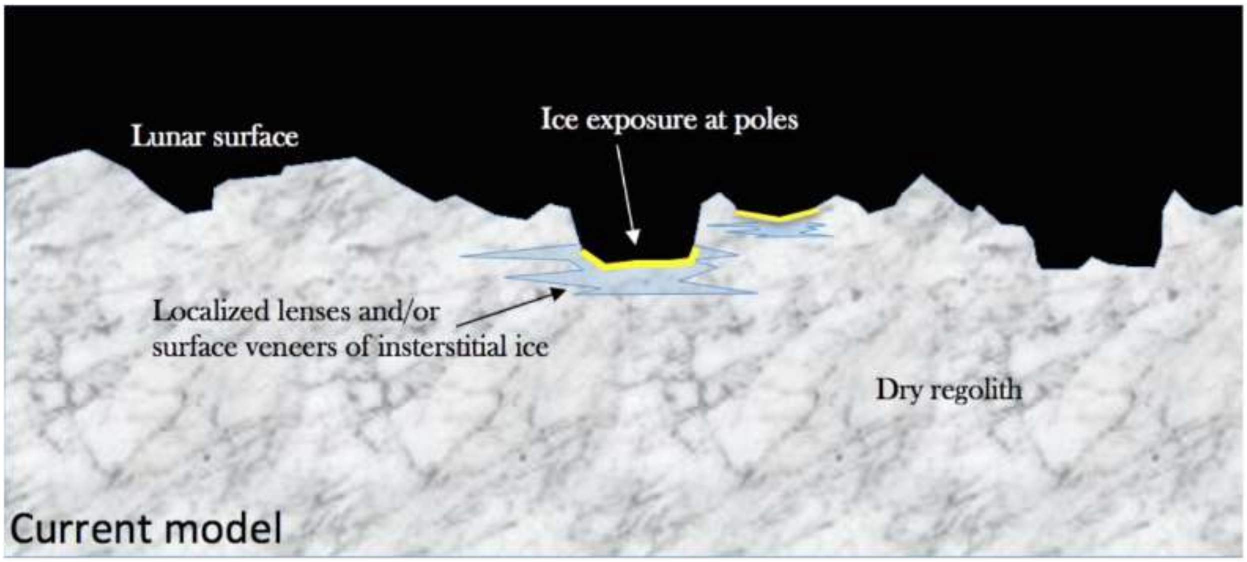
Journal of Space Operations & Communicator (ISSN 2410-0005), Vol. 21 No. 3, Year 2025

New Lunar Economy: A Prospectus on Lunar Ice Extraction

Ronald H. Freeman, PhD
Space Operations and Support Technical Committee, AIAA



The current model envisions the lunar polar ice as surface veneers of pure ice or of interstitial ice.

Abstract

There is large risk to investors deriving from inadequate experience in the lunar environment. Mining architecture will be more attractive to investors if startups begin operations and buy down risks from a minimum infrastructure starting point, and to then "smooth scale-up" to larger operations when the risks have been retired. For startup commercial operations capable of supporting NASA's Sustainable Exploration concept and the Artemis program, what is needed is the "Minimum Viable Product" (MVP) space mining method that starts at small size while still producing commercial revenue. This paper aims to explore options for which an MVP lunar mining proposal is both practical and energy efficient.

Keywords: Icy regolith mining, Lunar cold traps, Aqua Factorem, De dusting, NASA's Centennial Challenges Program (2021)

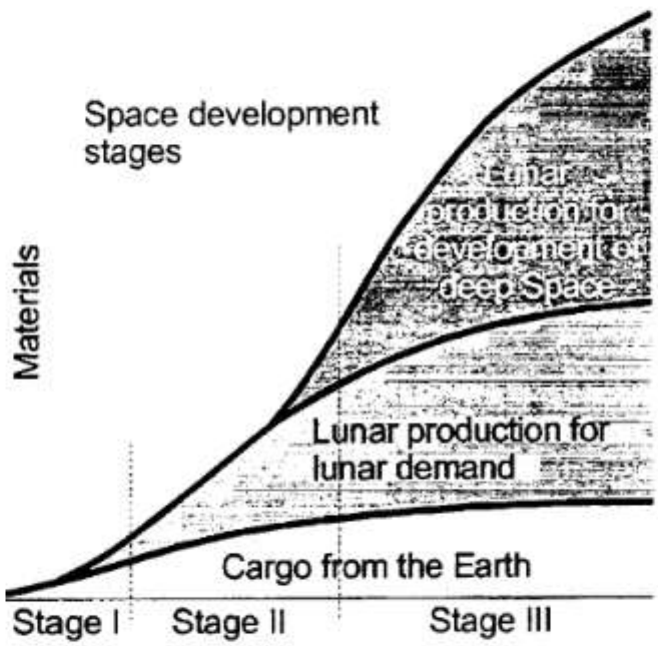
Background

The ice, originally reported in November 1996 from Clementine results for the south pole, appeared mixed in with the lunar regolith (surface rocks, soil, and dust) at low concentrations conservatively estimated at 0.3 to 1 percent. Subsequent data from Lunar Prospector taken over a longer period indicated the possible presence of discrete, confined, near-pure water ice deposits buried beneath as much as 18 inches (40 centimeters) of dry regolith, with the water signature being stronger at the Moon's north pole than at the south [1]. The ice was thought to be spread over 10,000 to 50,000 square km (3,600 to 18,000 square miles) of area near the north pole and 5,000 to 20,000 square km (1,800 to 7,200 square miles) around the south pole, but the latest results show the water may be more concentrated in localized areas (roughly 1850 square km, or 650 square miles, at each pole) rather than being spread out over these large regions. The estimated total mass of ice is 6 trillion kg (6.6 billion tons). Uncertainties in the models mean this estimate could be off considerably. Understanding the character and origin of lunar water-ice, and more generally of lunar polar volatiles, is one of seven broad science objectives identified by NASA's Artemis Science Definition Team [2]. Lunar polar cold traps, located within permanently and transiently shadowed regions (PSRs/TSRs), are of high priority for both volatile science and exploration. Evidence for volatiles on or underneath the surface of lunar cold traps has been found by the The Lunar Crater Observation and Sensing Satellite impactor mission [3], the Lunar Orbiter Laser Altimeter [4], the Diviner Lunar Radiometer Experiment [5], the Lyman Alpha Mapping Project [6], and the Moon Mineralogy Mapper [7]. However, the scientific instruments used in these studies are limited by their signal-to-noise ratio (SNR) and/ or resolution over PSRs and are only able to provide data and imagery within large PSRs (on a kilometer to sub-kilometer scale). The lack of direct illumination makes imaging of PSRs very challenging. Still, PSRs receive small amounts of secondary illumination, i.e., sunlight backscattered from surrounding topography and Earth, as well as faint illumination from stars [8].

1. Introduction

Rationale for terrestrial mineral exploration on the Moon is firmly entrenched within the context of economic gain, with asset valuation forming the primary feedback to decision making [9]. It is obvious that mining operations in space are necessary for two basic purposes:

1. Production of useful components (metals, He^{+3}, energy etc.) for sale in the Earth markets. Large-scale mining and power companies may finance and realize these works; and,
2. Maintaining the presence of mankind from mining materials and energy to construct extraterrestrial bases.



The type of mining, mainly "open pit", precedes regolith being processed. All the necessary cargo will be delivered from Earth during the first stage. The second stage begins with self-reproduction of lunar technological units, and large-scale construction of inhabited and industrial buildings. Hard rocks are involved in processing to the beginning of the third stage when production capacity expands to constructing platforms and spacecraft intended for interplanetary travel. A lot of these excavation methods are in use today for industrial applications, so they are at least proven to be feasible, but dust generation is quite an issue. This means that systems such as bucket drums and augers are much more feasible, but these have their own drawbacks, such as the fact that bucket drums need to dump their contents after a while and an auger can clog, which is quite a problem for autonomous operations on the Moon. Regolith is an amalgamation of sand, grains and particles. Countless different minerals, including water (ice), can be found by analyzing the regolith structures. In order to effectively isolate the different coarse grains, it is necessary to crush and separate the large rocks of regolith found on the surface of the Moon. Pieces of regolith boast a variety of hardness levels based on the mining depth and ice percentage present within the rock. Therefore, different types of crushers need to be employed for the mining of regolith with specific hardness.

With regards to the ideas introduced by NASA, using a central crushing facility would require excavating and hauling large regolith blocks between 2 and 8 mass percentage water ice, which is very inefficient. It is therefore better to crush the regolith on site and extract water there. Furthermore, in order to avoid the sublimation of the ice on the surface, ice should be found at a depth of 11 cm and below. Finally, extracting regolith through methods that induce a phase change is inefficient, as to change the phase of the ice. It is necessary to use high-power, low-efficiency devices that produce a lot of heat. Such subsurface ice regolith has the hardness of rock. So, in order to avoid phase changes of the ice, it needs to be crushed. This requires appropriate machinery, so-called crushers. In order to investigate the efficiency and capacity of these crushers, it is first necessary to classify the hardness of the rocks. This is done according to the ice percentage present within a specific piece of rock. For example, rocks with less than 2% ice are classified as soft rocks, a hardness around 2.0. An ice percentage of 8% yields rock with a hardness of around 4.0, classifying them as rocks of moderate strength. Finally, any rock that contains 10% ice or more is deemed a hard rock, with a hardness exceeding 8.0. The type of crusher used depends on the hardness of the rock: jaw and cone crushers are to be used for strong rocks, while moderately hard rocks can be handled by roll crushers. Highly efficient, small crushers called impact crushers can be used for softer rocks. Impact crushers are preferred, as they boast the highest efficiency among all the machines. An experiment conducted on Earth regarding this method consists of a two-stage method: an impact crusher is used, followed by separation of ice crystals using centrifugal force. Energy consumption of thermal extraction is in the range of tens of kilowatts (kW). Comparing this crushing method that assures no phase change of the ice with thermal extraction, it becomes clear that crushing and sieving is far more efficient in terms of energy consumption. The proposed crushing solution can extract 100 kg of ice per day with an energy consumption of 118 W. This is comparable to the Aqua Factorem system and far more efficient than the thermal extraction methods, as these have a power consumption at a minimum of 6500 W for a little over 100 kg of ice. The drawback of this approach is that crushers operate on extremely hard materials frequently and in quick succession, leading to a lot of wear and tear in the material that constitutes the crushers, as well as the sieve. It is unclear how long one crusher could last while continuously mining rocks and extracting ice [10].

The Moon's regolith structure is assumed to be fractured due to the long-term impact of micrometeors hitting the Moon's surface. The Aqua Factorem extraction method aims to take advantage of the fact that the ice crystals are bound weakly to the rock grains at the surface. Therefore, it is possible to extract these surface ice crystals through minimal use of energy. On the other hand, the crushing and sieving extraction method focuses on mining ice at great depths to ensure the ice is extracted without phase change. By keeping the ice from melting, the hardness of the mined rocks is maintained, and it becomes possible to use crushers to grind the combination of ice and other grains into fine sand particles. From this point, it is possible to separate the ice particles through sieving. This method of separation is extremely energy efficient, as no energy is wasted on heating the regolith to extract ice [11.

Before a detailed mining and water extraction system can be designed, properties of the lunar water ice need to be accurately determined. The obvious choice is to send a robotic lander into the one of the lunar poles to directly measure some of the important characteristics of the ice. Alternatively, a lunar ice simulator would allow scientists to study the ice deposition process and measure the physical properties of ice and regolith mixtures for hardness, water-regolith cohesion, compressive strength, and shear strength, under conditions like those found in the cold traps near the lunar poles. On a larger scale, a simulator may provide a test bed for testing subsystems and complete systems for ice extraction [12].The large change in relative density with the increasing depth has to do with the impacts of small meteorites. Meteorites have stirred up the surface, making it loose at the same time compressing the underlying soil. In order to distinguish the many different lunar ice extraction methods, a classification system was created that evaluated both benefits and constraints. The first distinguishing trait was based on scales of energy required in the types of processes used. This type consisted of three branches: 'Thermal Extraction', 'Mechanical Extraction', and 'Chemical'. Most lunar ice mining concepts depend on thermal extraction based on the assumption that it will be easier than strip mining with robots in the dust. The problem with thermal extraction is two-fold. First, the energy budget is gigantic. Most of the energy is wasted heating the lithic fraction of the regolith. The high energy requires either nuclear fission or significant infrastructure to bring solar energy into PSRs with associated increase in both risk and cost for infrastructure maturation and lunar deployment. Second, water vapor in lunar regolith is driven away from a heat source, not toward it, as both experiments and modeling [13] show. So, most of the vaporized ice re-freeze elsewhere in the soil rather than being extracted. Driving the vapor in the correct direction requires either additional heating of the subsurface to create thermal gradients to overcome pressure gradients (if that is possible) or containment such as by physically drilling a core tube into the subsurface. Most thermal extraction methods require anywhere from a few kW to a few hundred kW to operate (kilowatt range), whereas mechanical extraction methods are around a few W to a few hundred W (watt range). Chemical methods are usually used in conjunction with other methods (such as thermal or mechanical) to produce water (alternatively hydrogen or oxygen) [14].

Aqua Factorem

Just like all minerals and rocks on the Moon, it has been broken into fine grains and mixed with the other lithic fragments in the soil [15]. This is a gigantic advantage to lunar mining. Not only has nature already provided a gigantic quantity of energy into the PSRs to break the ice into fine pieces, but it has done so at a very low flux spread over a very long period. So, much of the ice remained solid and still exists in the soil. If we can sort the different crystalline phases from one another without phase change, then we can transport just the volatiles out of the PSRs to process in the sunlight where energy is available, avoiding most of the infrastructure and cost. To perform this, we have innovated Aqua Factorem, a combination of pneumatic separation, magnetic separation, and electrostatic separation that operates with low power and low equipment mass in a PSR.

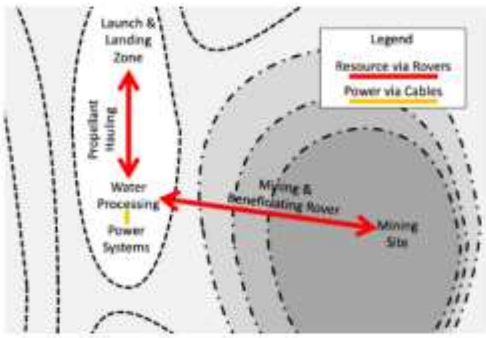


Figure 1: Relationship of Hardware Elements, Option 1

An enhancement to this basic power system is to move the water cleanup plant partway into the PSR using a superconducting cable to bring the solar power to the plant. This will shorten the driving distance of the mining rovers. A second rover can transport clean water outside the PSR for electrolysis in the sunlit area. This will be beneficial if the beneficiation process is unable to achieve the highest levels of concentration for the water ice.

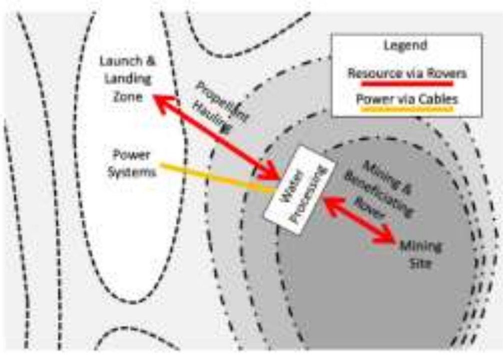


Figure 2: Relationship of Hardware Elements, Option 2

Another possible version is to take the beneficiating systems off the rover and place them in a separate unit that will deploy one time into the PSR near the mining site then remain stationary. Superconducting cables will provide power to the beneficiate from outside the PSR. The mining rover will recharge by plugging into the beneficiating system or by receiving recharged fuel cells that were transported in by the propellant hauling rover(s). The water processing system can be located outside the PSR near the power system.

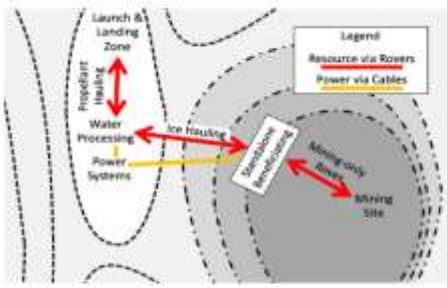


Figure 3: Relationship of Hardware Elements, Option 3

There are two concerns about the physical state of the ice. The first is whether the ice exists in solid lenses or in a form that bonds the soil together into a competent solid, which at the cryogenic temperatures of the PSRs would be as hard as rock. If that were the case, then an excavation approach may not be viable. The second concern is whether the ice, although in granular form (either loose grains or only weakly cemented grains and thus excavatable), might exist in polymineralic grains, bonded as a solid icy coating onto the lithic grains. If these concerns were realized, then beneficiation would depend very heavily on high-force digging methods (such as the Low Energy Planetary Excavator digging implement developed by Orbitec16, which uses a cutterhead that is adaptable to digging conditions to minimize energy use) and/or extensive grinding to liberate the ice before beneficiation [16]. A particular version of this novel ice extraction method is shown in Figure 5.

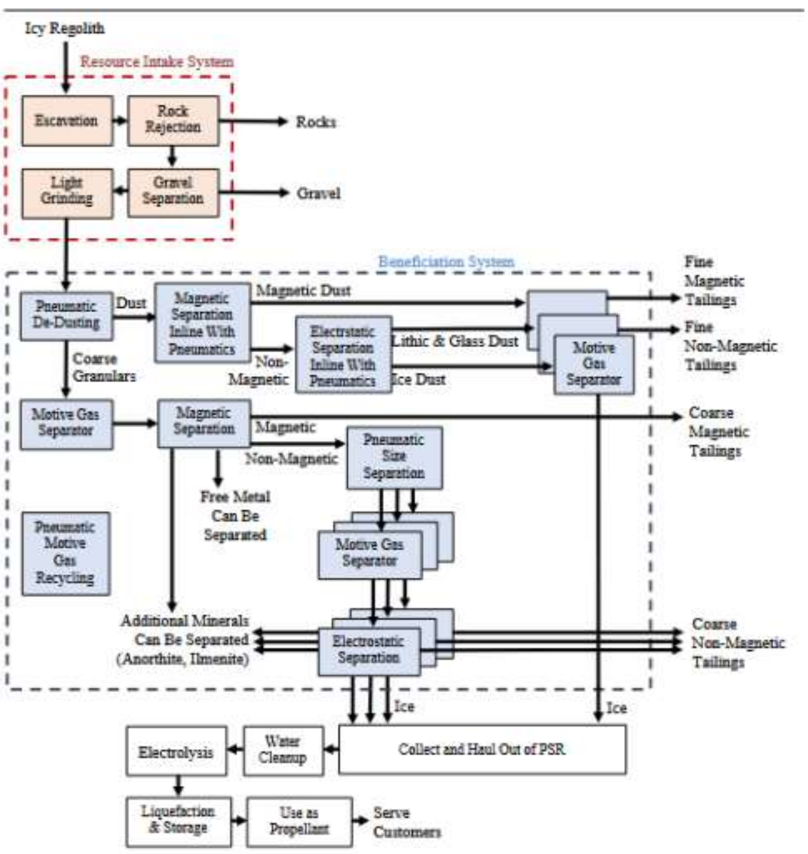


Figure 5. Water Extraction and Propellant Manufacture Method

A robot scoops the regolith with rock-rejection and gravel separation to pass only fines. A grinder fractures the weaker particles, liberating ice fragments from mineral and lithic fragments. This Resource Intake system transfers the regolith into a batch-processing Beneficiation System, with pneumatic separation, magnetic separation, and electrostatic separation combined in a sequence that can handle the exotic lunar geology. The system outputs separated streams of ice grains and slag soil particles. The beneficiation process can be extended to also separate free metal particles and specific mineral grains of high resource value. The soil is 95-98 wt% non-ice (“tailings”), which is dropped in the PSR while the desired 2-5 wt% of ice is transported to sunlight. This kilometers-long transport is made economically viable by the extreme mass reduction that took place in the PSR. The water cleanup, electrolysis, liquefaction, and storage stages are included in every ice mining architecture but now they are in a location with energy. After hauling the resource to sunlight, the rover recharges or swaps out its batteries or fuel cells then returns to the PSR. In addition to transporting the resource, it also hauls fuel cells into and out of the PSR There are locations in the Moon’s poles where driving distances from sunlight to the ice resource are just a few kilometers on gentle slopes [17], Ice concentrations in these “Type 2” locations [18] are expected to have a shallow dry overburden of about 30-50 cm that must be removed.

Variations on this architecture can later be added to extend its reach into the deeper PSRs where ice has higher concentrations and less overburden. For example, additional fuel cells can increase driving distance, or, with solar energy towers as innovated [19] mining and processing could be done entirely inside PSRs (no driving back to sunlight). Still, using beneficiation instead of thermal extraction will vastly reduce the energy, infrastructure, and the cost, thus improving the economic benefit. To crudely illustrate the benefit, United Launch Alliance (ULA) study [20] calculated that 800 kW thermal energy is needed to extract 2,450 t of water yearly to support the future commercial demand for lunar water. Producing 2,450 t of water yearly at 5% concentration requires processing 49,000 t of regolith yearly or 1.55 kg/s. If sunlight with a duty cycle of 70% in a polar location, provides only 2% yield, it must be processed at 5.55 kg/s to make up the difference. Assuming a larger scale beneficiator processes 3 kg/s (ten times the pilot plant goal), then with a mining/hauling duty cycle of 50% the operation would require 4 of them. With each operating at 5 kW, this is a 97.5% power reduction versus thermal extraction. With subsequent processes taking place in the sunlight, there is potentially >99% reduction of total energy and infrastructure in the PSR.

After lunar regolith is excavated and water extracted, consideration is given to one ice extractor pairing with a few excavators. The major type ’Mechanical Extraction’ may be further subdivided into ’Beneficiation’ and ’Crushing and Sieving’. Beneficiation is a concept pertaining to the separation of material of higher value from unwanted material [21]. De-dusting is a common first step in terrestrial beneficiation processes for recycling and will be an important first step in lunar gravity affecting poor flowability of the cohesive dust fraction. For the downstream separation processes to be efficient, the particles must easily flow, and the dust removed. Also, lunar dust has a high surface area to mass ratio so the superparamagnetic npFe in their glass patina makes their response to magnetic fields more dominant compared to the coarser particles. Their large surface areas make for easy adhesion to larger particles via the van der Waals forces. If dust adheres to ice particles, then ice to be misclassified into the magnetic slag. The large shear force of the gas in the entrainment process inside an eductor separates dust from the surfaces of larger particles so that dust is separated and removed.

De-dusting is ordinarily accomplished in industry via pneumatic separation. Pneumatic separation can be used more generally to separate material into any arbitrary number of particle size ranges, and this is leveraged in the version of Aqua Factorem shown in Figure 5. That figure shows pneumatic de-dusting as a separate process before the magnetic separation, followed by separation of the motive gas precedes before magnetic separation, after which entrainment in a pneumatic separator occurs a second time for pneumatic size sorting. The possible benefit of doing the pneumatic sorting in two stages before and after magnetic separation, is that the extremely efficient magnetic separation requires no size sorting prior to magnetic separation for greater efficiency. The dust stream output of the De-Dusting stage contains ice that should be recovered. The first step is to remove the magnetic fraction of the dust. Most lithic/glass dust particles are highly magnetic regardless of their chemical composition due to the nanophase npFe that builds up in their surfaces through space weathering. The De-Dusting process delivers coarse granules through a motive gas separator (a cyclone) into a hopper to feed into the magnetic separator. The purpose of this stage is to reduce the bulk of material prior to the size classification and electrostatics, to make those processes more efficient. Granular magnetic processing is extremely fast and efficient, and it reduces the bulk material significantly The dust fraction that should be removed to improve soil flow is about 20 μm and finer, which constitutes roughly 29.7 wt% of the mass of the lithic material. This will split the ice at roughly 60 μm. So, if ice constitutes only 5 wt% of the bulk soil, then per each of the models, the fraction of the resource and the fraction of mass in each stream will be the ice resource, are shown in Table 4.

Ice Model	Fraction of the Total Ice in the Dust Stream (wt%)	Fraction of the Mass in the Dust Stream That Is Ice (wt%)
1	64.5	10.4
2	54.7	8.9
3	21.2	3.7
4	9.4	1.7

Table 4. Results of model calculations for de-dusting.

Problem
According to NASA's Human Integrated Design Manual estimates, a 118 L of water is needed to support a crew of 18 people with regenerative live support, or 6.47 kg per crew member per day [22]. A key challenge in establishing a permanent human presence on the Moon is securing a reliable, local source of water or ice used as a propulsion, oxygen and drinking water source. Transporting water from Earth is extremely expensive, about $2000 to $20000 per kg [23]; so, it is much more economical to extract it on site. It is expected that for each square meter of a deposit, there should be five more liters of ice within the top one meter of regolith, compared to areas surrounding the deposit [24].

There is large risk to investors deriving from inadequate experience in the lunar environment. Mining architecture will be more attractive to investors if they can begin operations and buy down risks from a minimum infrastructure starting point, to then have a smooth scale-up to larger operations when the risks have been retired. For startup commercial operations capable of supporting NASA's Sustainable Exploration concept and the Artemis program, what is needed is the "Minimum Viable Product" (MVP) space mining method that starts at small size while still producing commercial revenue, [25]. Incremental scale-up to large size coupled to progressively bringing-down risks, assures that the initial technology is not dead-end. The larger scale infrastructure to operate deeper in PSRs may be more easily funded after the MVP mining operation has proven successful.

Purpose
This paper aims to explore options for which an MVP lunar mining proposal is both practical and energy efficient.

2. Methodology and Results

A literature search was surveyed for models and design architecture proposals relevant to lunar ice mining. MVP mining operation in PSRs proven successful, resulted in fundings as summarized below. For example, the design philosophy behind the Aqua Factorem architecture took advantage of the natural lunar environment rather than treating it as a foe to be defeated. Survey results are summarized in the following tables.

- Characterization of lunar ice was provided in a literary search with the following findings.

The ice that was deposited hundreds of millions to billions of years ago in the lunar cold traps would have frozen as hard as granite. Lunar ice is just another mineral [26].
Grains of crystalline ice are most likely in the ~10-100 μm size range based on M3 Near Infrared (NIR) reflectance spectra indicating ~70 µm ice grains on the surface vapor deposition, and NIR spectral bandwidth and position of LCROSS ejecta indicating the ice from depths where crystallized particles had a ~8 µm mean size [27], [28], 29].

Location of the greatest lunar ice concentrations.

Per McClanahan's model and analysis, the greatest ice concentrations located near PSR's coldest regions below 78º K or -198º C, and near the base of the PSR's poleward-facing slopes [30].
On the Moon, there exist only solid and gaseous forms of water due to the ultra-cold environment and near vacuum pressure. If the temperature is below 150K, water always exists in solid form [31].

Not determined if the PSR's ice deposits are buried under a dry layer of regolith [32].
Not determined the volume of the PSRs' ice deposits. Expected that for each surface 1.2 square yards (square meter) residing over these deposits there should be at least about five more quarts (five more liters) of ice within the surface top 3.3 feet (meter), as compared to their surrounding areas [33].

- Characterization of lunar regolith.

Relative density on the surface is set to 0%. In the first 15 cm, the relative density was 65%; from 30 to 60 cm, it was 92% [34].
Billions of years of (micro-)meteoroid bombardment has finely broken all the crystalline solids within a well-understood depth of the regolith's surface [35].
Lunar geology model demonstrated how lunar ice broke apart into individual ice grains and mixed into the lunar regolith like the grains of the other minerals [36].
Grains of crystalline ice are most likely in the ~10-100 μm size range based on M3 Near Infrared (NIR) reflectance spectra indicating ~70 μm ice grains on the surface vapor deposition [37].

NASA's Centennial Challenges Program (CCP)

The literature search also reviewed how NASA ongoing efforts in developing and maturing excavation and transportation technologies operated in the extreme environmental conditions at lunar south pole [38]. NASA's Centennial Challenges Program (CCP) incentivized innovative approaches for excavating icy regolith and delivering water in extreme lunar environments. In Phase 1, system architecture should maximize water delivery while minimizing energy use and the mass of equipment required for lunar surface transport. The challenge rules described a hypothetical icy-regolith profile consisting of 0.2m thick top layer of dry regolith, following a 0.8m thick layer of regolith containing 4% water by weight, followed by a 2.5m thick layer of regolith containing 10% water by weight as shown in Figure 2.

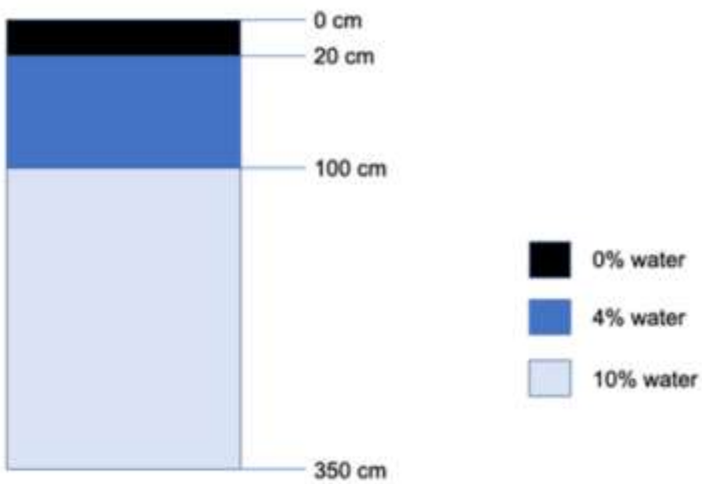


Fig. 2 Percentage of Water in Icy Regolith at various depths.

Competing teams were required to calculate the energy required for collecting water based on their chosen architecture design and how deep their architecture was designed to reach below the surface. The deeper 10% icy regolith contained more water but required more energy to access. Roughly 74% of the submitted architecture designs accepted the energy penalty and targeted the deeper and more resourceful 10% icy regolith. Site preparation plans included plow blades and robotic arms to clear rocks and boulders or microwave sintering equipment for road building and dust mitigation. Several teams proposed digging or scraping equipment to remove the dry regolith overburden which does not contain any water content. One architecture a team proposed was setting up elevated beacons for high resolution local positioning along with ground penetrating radar for detailed mapping of subsurface obstacles. And another proposed placing a rail system on the surface for transportation to minimize dust interaction and to reduce travel times. The Challenge rules required competing teams to access the icy regolith within a specific permanently shadowed crater on the lunar surface. Ground contact digging implement designs included bucket ladders, bucket drums, grinders, rippers, tillers, augers, coring drills, draglines, hammers, scrapers, and scoops. Most of the proposed architectures operated on the relatively level ground at the bottom of the shadowed crater, but a few were specially designed to take advantage of the sloping walls of the crater by mining or tunneling directly into the crater walls. A few architectures proposed, suggested ultrasonic energy or vibratory action to their ground contacting implements to assist with the excavation process. The Challenge rules allowed competing teams to utilize an optional NASA-provided water extraction plant to separate water from icy regolith. Landed mass, flow rate limitations, and power usage specifications for this optional processing plant were included in the Challenge rules. This optional plant was required to be located 200 meters from the center of the excavation site, so teams who chose to utilize this plant had to include transportation of icy regolith between the excavation site and the plant. Surface rovers containing onboard hoppers or dump beds were a common solution among competing teams. The Challenge rules required competing teams to transport processed water from the processing site to a water delivery site which was located more than 3 kilometers away and included nearly 0.5 kilometers of elevation change. Competing teams designed and submitted a wide variety of innovative transportation architectures. Some teams chose to transport the precious resource in liquid water form, while others chose to transport frozen water-ice. Teams who chose to transport the water in liquid form, explained how their architecture kept the liquid water from freezing during the trip. Some of the proposed ice transport architectures protected the ice from sublimation during the trip, while some teams chose to accept some sublimation losses and transport the ice in open rover beds.

The submitted architecture designs included many different creative and innovative robotic teams. Some architectures performed their entire mission using only a single flexible and highly capable robot, while others utilized a suite of different styles and types of robotic workers. Several teams proposed a single robot that was capable of both excavation and transportation. Many teams chose to include task focused robot styles, like excavators that only excavate and haul. Some teams chose to use the same robot to haul icy regolith from the excavation site to the water extraction plant and to haul ice from the processing plant to the delivery site. But some teams chose to include a third robot type to haul water from the processing plant to the delivery site. The distribution of work was also varied between the competing team’s submissions. Some teams chose to operate just one excavator robot, for example. While other teams chose to utilize multiple parallel excavation robots. Several competing teams submitted an architecture that included special robots and equipment dedicated to the initial setup of that architecture. Some even included equipment dedicated to unloading the rest of the rovers and equipment from the lunar lander which delivered that architecture to the lunar surface. Teams were asked to consider maintenance and repair options for their proposed architecture. Many teams proposed rechargeable or exchangeable battery packs. Some proposals included special robots, robot arms, and related equipment dedicated to maintenance and repair of that architecture. Several architecture designs included sharing of parts or subsystems between multiple robot types. For example, common chassis, mobility, power, wheel, bearing, excavation components, transportation components, and avionics modules were proposed. The submitted architecture designs included many different creative and innovative power options. Many competing teams proposed recharging their transportation rovers at the NASA-provided water extraction plant.

On August 18, 2021, NASA announced $500,000 in awards for 13 winning teams [39]. The winners included a mix of well-known players in space technologies and newcomers that had not previously worked with NASA on excavation and transportation technologies. Table 1 summarizes the winners, prizes, and awards.

Team	Location	Prize	Award
Redwire Space	Jacksonville, FL	1st place	$125,000
Colorado School of Mines	Golden, CO	2nd place	$75,000
Austere Engineering	Littleton, CO	3rd place	$50,000
AggISRU	College Station, TX	Runner up	$25,000
Aurora Robotics	Fairbanks, AK	Runner up	$25,000
Lunar Lions	New York, NY	Runner up	$25,000
OffWorld Robotics	Pasadena, CA	Runner up	$25,000
Oshkosh Corporation	Oshkosh, WI	Runner up	$25,000
Rocket M	Mojave, CA	Runner up	$25,000
Space Trajectory	Brookings, SD	Runner up	$25,000
AA-Star	Redmond, WA	Runner up	$25,000
LIQUID	Altadena, CA	Runner up	$25,000
Terra Engineering	Gardena, CA	Runner up	$25,000
TOTAL AWARDED			**$500,000**

Table. 1 Summary of Break the Ice Lunar Challenge Phase 1 Winners

Austere Engineering of Littleton, Colorado, won third place and $50,000 for its Grading and Rotating for Water Located in Excavated Regolith (GROWLER) system. The GROWLER system is based on rugged and proven terrestrial equipment but is designed to be as lightweight as possible. The architecture includes three excavation rovers, two ice transportation and maintenance rovers, twelve lunar positioning posts, and associated spare parts. The GROWLER system will first establish a local positioning system that it will be used for localization. Then it will use a combination of laser sensors and ground penetrating radar to map both the surface and the subsurface. This system will locate and avoid surface obstacles during setup, excavation, and transportation phases of the mission, plus it will also point out any large underground rocks which might obstruct excavation.

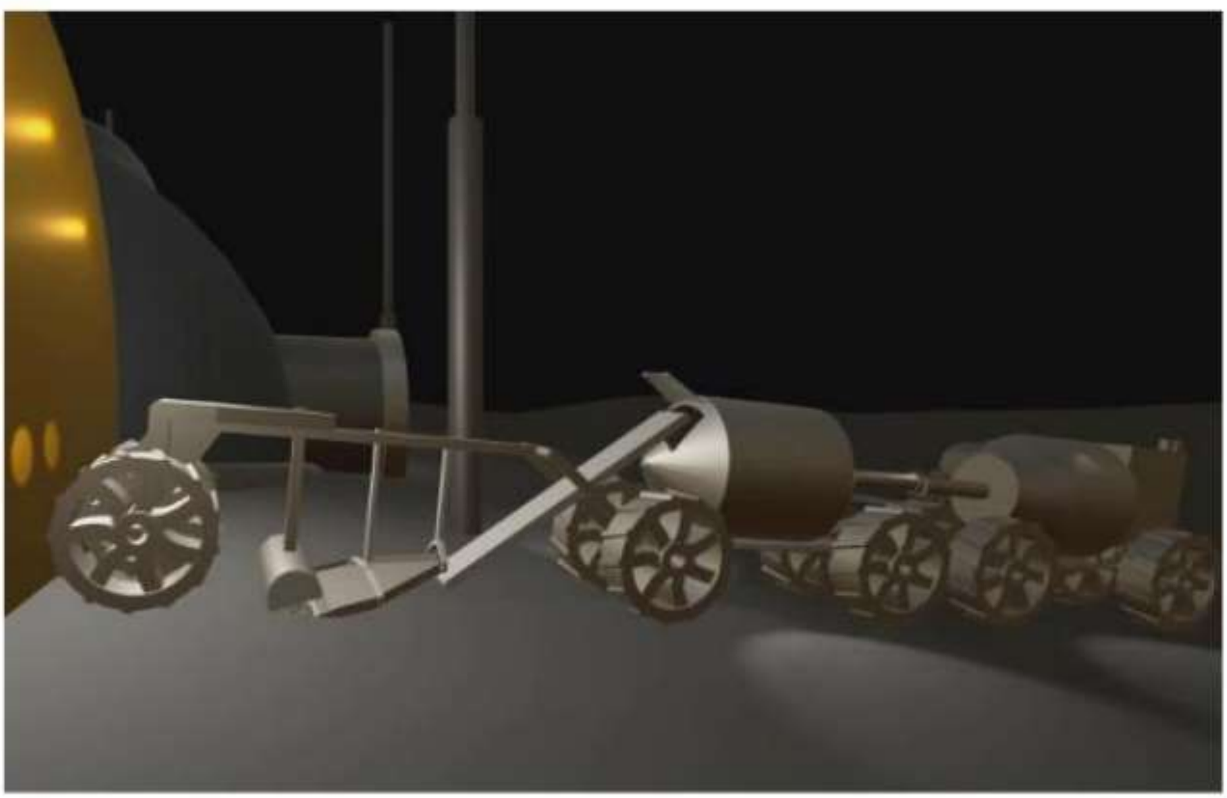


Fig. 11 GROWLER's system performing water transfer operations.

Each GROWLER excavator rover will scrape and clear the dry regolith overburden to expose the icy regolith. Then, they will utilize an onboard rotary tiller to break up the icy regolith along with a grating blade to scoop the broken material onto a conveyer system. The conveyer system will move the icy-regolith material into an onboard extraction drum. Once full, each excavator rover will drive to the power plant which is located near the excavation site where the ice transportation and maintenance rovers are waiting. An ice transportation and maintenance rover (see Fig. 11) will connect to the excavator rover for water transfer operations. To make water from the icy regolith, the excavation rover will heat up the onboard extraction drum and pump the resulting water vapor into the ice transportation and maintenance rover's onboard ice drum. During the heating operation, the extraction drum will rotate to guarantee that all the water is released from the regolith. After the water transfer is complete, the excavation rover will dump the dry regolith near the power plant and return to the excavation site for more excavation operations. Once full of water, the ice transportation and maintenance rover will deliver and deposit the water about 3 kilometers away to the delivery site which is also 0.5 kilometers higher in elevation.

3. Discussion

A robotic sample return mission could bring ice back to Earth for study, perhaps followed by a human mission for more detailed sampling. The simple fact that the ice is there will help scientists constrain models of impacts on the lunar surface and the effects of meteorite gardening, photodissociation, and solar wind sputtering on the Moon. Beyond the scientifically intriguing aspects, deposits of ice on the Moon would have many practical aspects for future manned lunar exploration. There is no other source of water on the Moon, and shipping water to the Moon for use by humans would be extremely expensive ($2,000 to $20,000 per kg). The lunar water could also serve as a source of oxygen, another vital material not readily found on the Moon, and hydrogen, which could be used as rocket fuel. Paul Spudis, one of the scientists who took part in the Clementine study, referred to the lunar ice deposit as possibly "the most valuable piece of real estate in the solar system". It appears that in addition to the permanently shadowed areas there are some higher areas such as crater rims which are permanently exposed to sunlight and could serve as a source of power for future missions [40].

Satellite data on the lunar surface provides a lot of information about mineral resources, but without in situ research it is not possible to accurately estimate their size and whether their exploitation will be economically profitable. Until the deposit is confirmed in situ, e.g., by geological drilling with core collection, only probable deposits can be considered. In the case of satellite imaging of the Moon's surface, a big problem is that the space missions to date have been mainly scientific missions and the resolution of the obtained images (in the order of tens of square kilometers per pixel) does not meet industrial requirements. Currently, over 250 lunar missions, both commercial and scientific, are planned for the next decade [41]. Given the enormous operational depth of the lunar surface, the bottleneck is the lack of a communication and navigation system for future missions. However, work is underway to solve this problem. ESA, working on the ESA Moonlight communications and navigation constellation [42], will activate the development of a space economy worth EUR 100 billion and invite companies to create the system and services based on it. Lockheed Martin, and more specifically Crescent, a company belonging to Lockheed, is also working on a communication and navigation system called Parsec [43]. Lockheed Martin, together with General Motors [44], is also working on the next generation of lunar rovers. However, commercial exploration of the Moon's south pole will be a great technological challenge. In the Apollo program, humans landed on the Moon in carefully selected locations near the equator, The Δv needed [45] was the lowest (~850 m/s), while in the case of the poles, Δv will be ~1200 m/s. Since the amount of energy consumed by a rocket is proportional to the square of the change in its speed Δv, the landing in the polar regions will require almost twice as much energy, therefore, more fuel. Another challenge will be large differences in height, which in some lunar craters are greater than even the highest peaks of the Himalayas [46]. Moreover, the slopes of craters on the Moon can be steep. All this may prevent the safe entry/exit of an exploration rover to/from the crater, not to mention large mining trucks. There may also be stones and other natural obstacles on paths, making it impassable. The rover will consume more energy when climbing steep slopes, which may lead to premature discharge of its battery. Most rovers used for space exploration are powered by photovoltaic cells that charge the batteries on board. There are examples of rovers powered by an RTG (Radioisotope Thermoelectric Generator), but these are exceptions rather than the general rule. Moreover, the RTG generates little electricity (about 100 W); although, including the heat generated, its power is significant (about 1 kW). Many problems would be solved by using nuclear reactors. Unfortunately, the EU is very hostile to the use of nuclear energy in space for fear of possible environmental contamination.

Startups must have a bold risk culture, which manifests in risk openness project management models. For example the Agile methodology, breaks projects into several “sprints” and delivers a Minimum Viable Product (MVP) at the end of each sprint [47]. Due to their reusability, SpaceX’s Falcon 9 (F9) and Falcon Heavy (FH) launchers have lowered the cost to orbit offered to third parties by a factor of 3-6 with respect to other Western, Russian, and Chinese launchers. F9 capacity to low Earth orbit (LEO) is about 20 tons, at an advertised cost of about 62M$, that is about $3000/kg [48]. Large numbers of quality control procedures aim to reduce the risk of failure. As an example, the ECSS (European Cooperation for Space Standardization) manuals commonly used by ESA and other European space agencies foresee that > 15000 requirements for standard missions (e.g. Euclid) have to be met, mostly on quality standards. This is an expensive and time-consuming procedure that greatly reduces the probability of failures but does not eliminate them. Moreover, only a few companies win contracts for major science missions, effectively introducing a monopoly, which inflates costs. As an example, the main prime contractors of ESA missions alternate between two companies (Thales-Alenia Space and Airbus). Space exploration missions that are developed on timescales of years instead of decades can respond in a much timelier way to emerging scientific problems. More frequent space missions can revolutionize the way space science is done because they can trigger a virtuous loop between opening up new fields of investigation and finding timely responses to the new questions.

4. Conclusion

Before implementing existing and proposed methods of regolith excavation and water ice extraction for lunar in situ resource utilization Minimum Viable Product (MVP) cases, a planned survey of icy regolith characterized localizations and the energy costs in the mining required comparative analyses. It began with a background on the availability and physical form of water on the Moon, then categorization and evaluation of subsequent efficiency-// energy-valued extraction techniques were cost-/ time- compared. Each method was assessed based on mass, time, and power efficiency. Crushing and sieving techniques of the icy regolith provided a basis for MVP sorting and further refinement of their by-products. In highlighting both established technologies and recent innovations, this review will guide future research and engineering efforts toward efficient lunar resource utilization. [49]. NASA’s Centennial Challenges Program (CCP) incentivized lunar startups to develop and propose innovative approaches for excavating icy regolith and delivering water in extreme lunar environments.

References

[1] Feldman et al. (1998), Fluxes of fast and epithermal neutrons from Lunar Prospector: Evidence for water ice at the lunar poles. *Science, 281*,1496.
[2] National Aeronautics and Space Administration. (2020). Artemis III science definition team report. *Report No. NASA/SP-20205009602*.
[3] Colaprete, A. et al. (2010). Detection of water in the LCROSS ejecta plume. *Science 330*, 463–468
[4] Rubanenko, L., Venkatraman, J., & Paige, D. A. (2019), Thick ice deposits in shallow simple craters on the Moon and Mercury. *Nat. Geosci. 12*, 597–601
[5] Paige, D. et al. (2010), Diviner lunar radiometer observations of cold traps in the Moon’s south polar region. *Science 330*, 479–482.
[6] Gladstone, G. et al. (2012). Far-ultraviolet reflectance properties of the Moon’s permanently shadowed regions. *J. Geophys. Res. 117*, E00H04.
[7] Li, S. et al. (2018). Direct evidence of surface exposed water ice in the lunar polar regions. *Proc. Natl Acad. Sci. USA 115*, 8907–8912.
[8] Kloos, J., Moores, J., Godin, P., & Cloutis, E. (2021). Illumination conditions within permanently shadowed regions at the lunar poles: Implications for in-situ passive remote sensing. *Acta Astronaut. 178*, 432–451
[9] Blair, B. (1999). Economics of lunar materials exploration. Lunar polar ice: Methods for mining new resource for exploration. In *37th Aerospace Sciences Meeting and Exhibit*.
[10] Coppus, B., Fisekovic, M., Passon, T., Pujanek, M., & Verweij, I. (2025). *Lunar Ice Extraction Methods*.
[11] Coppus, B., Fisekovic, M., Passon, T., Pujanek, M., & Verweij, I. (2025). *Lunar Ice Extraction Methods*.
[12] Gustafson, R., & Rice, E. (1999). Lunar polar ice: Methods for mining new resources for exploration. In *37th Aerospace Sciences Meeting and Exhibit*].
[13] Brisset, J., Miletich, T., & Metzger, P. (Feb. 2020). Thermal extraction of water ice from the lunar surface – A 3D numerical model,” accepted for publication at *Planetary and Space Science*
[14] Sargeant, H. et al. (2021). Hydrogen reduction of lunar samples in a static system for a water production demonstration on the Moon. In: *Planetary and Space Science 205*, p. 105287.
[15] Hurley, D., Lawrence, D., Benjamin, D., Bussey, J., Vondrak, R., Elphic, R., & Gladstone, G. (2012). Two-dimensional distribution of volatiles in the lunar regolith from space weathering simulations. *Geophysical Research Letters 39*(9).
[16] Metzger, P., Sapkota, D., Fox, J., & Bennett, N. (2021). *Aqua Factorem: Ultra Low Energy Lunar Water Extraction* (No. Grant Number 80NSSC 20K1022).
[17] Elliott, J., A. Austin, P., Metzger, P., Sherwood, B., & Smith, M. (2019). Operations Modeling of Lunar Base Architectures, poster. *Lunar ISRU 2019 - Developing a New Space Economy through Lunar Resources and Their Utilization*, Columbia, MD, July 15-17, 2019.
[18] Austin, A., Sherwood, B., Elliott, J., Colaprete, A., Zacny, K., Metzger, P., ... & Vendiola, V. (2020). Robotic lunar surface operations 2. *Acta Astronautica*, *176*, 424-437.
[19] Sercel, J. (2019). Lunar-Polar Propellant Mining Outpost (LPMO): Affordable Exploration and Industrialization. *NIAC 2019 Phase I, Phase II, and Phase III Selections*.

[20] Kornuta, D., Abbud-Madrid, A., Atkinson, J., Barr, J., Barnhard, G., Bienhoff, D., ... & Zhu, G. (2019). Commercial lunar propellant architecture: A collaborative study of lunar propellant production. *Reach*, *13*, 100026.
[21] Coppus, B., Fisekovic, M., Passon, T., Pujanek, M., & Verweij, I. (2025). *Lunar Ice Extraction Methods*.
[22] Williams, D. (Jan. 2022). *Ice on the Moon*. Retrieved from nssdc.gsfc.nasa.gov.
[23] Williams, D. (Jan. 2022). *Ice on the Moon*. Retrieved from nssdc.gsfc.nasa.gov.
[24] Steigerwald, W. (Oct. 2023). Retrieved from www.science.nasa.gov.
[25] Bennet, N. (2019)]. An Existing Market for Lunar Propellant - GTO Orbit Raising as a Service, In: *Lunar ISRU 2019: Developing a New Space Economy Through Lunar Resources and Their Utilization*, LPI #2152. July 15-17, 2019, Columbia, Maryland.
[26] Gertsch, L. Gertsch, R., & Gustafson. R. (2006). Excavatability of Lunar and Martian Regolith: Initial Laboratory Tests on JSC-1 Simulants." In *Golden Rocks 2006, The 41st US Symposium on Rock Mechanics (USRMS*). American Rock Mechanics Association.
[27] Hurley, D., Lawrence, D., Benjamin, D., Bussey, J., Vondrak, R., Elphic, G., & Gladstone, R. (2012). Two-dimensional distribution of volatiles in the lunar regolith from space weathering simulations. *Geophysical Research Letters 39*(9).
[28] Li, S., & Milliken, R. (2017). Water on the surface of the Moon as seen by the Moon Mineralogy Mapper: Distribution, abundance, and origins. *Science Advances 3*(9) e1701471.
[29] Colaprete, A., Shirley, M., Heldmann, J., & Wooden, D. (2011, March). The Final Minute: Results from the LCROSS Solar Viewing NIR Spectrometer. In *42nd Annual Lunar and Planetary Science Conference* (No. 1608, p. 2037).
[30] Steigerwald, W. (2024). *NASA's LRO: Lunar ice deposits are widespread*. Retrieved from www.science.nasa.gov.
[31] Tian, Y., Tang, J., Jiang, S., Zhang, W., Pang, Y., Jiang, J., ... & Wang, D. (2024). Lunar regolith water ice simulation method and characterization. *Icarus*, *417*, 116119.
[32] Steigerwald, W. (2024). *NASA's LRO: Lunar ice deposits are widespread*. Retrieved from www.science.nasa.gov.
[33] Steigerwald, W. (2024). *NASA's LRO: Lunar ice deposits are widespread*.
Retrieved from www.science.nasa.gov
[34] Carrier, D. (2005). The four things you need to know about the geotechnical properties of lunar soil. In: *Lunar Geotechnical Institute*, pp. 2–9.
[35] Metzger, P., Sapkota, D., Fox, J., & Bennett, N. (2021). *Aqua Factorem: Ultra Low Energy Lunar Water Extraction* (No. Grant Number 80NSSC 20K1022).
[36] Hurley, D., Lawrence, D., Bussey, B., Rondrak, R., Elphic, R., & Gladstone, G. (2012). Two-dimensional distribution of volatiles in the lunar regolith from space weathering simulations. *Geophysical Research Letters 39*(9)
[37] Li, S. & Milliken, R. (2017): Water on the surface of the Moon as seen by the Moon Mineralogy Mapper: Distribution, abundance, and origins. *Science Advances 3*(9).
[38] Davidian, K. (2006). Prizes, Prize Culture, and NASA's Centennial Challenges. *4th International Energy Conversion Engineering Conference and Exhibit (IECEC)*, AIAA 2006-4074, San Diego, CA, 2006
[39] Mohon, L. (August, 2021). *NASA Awards $500K in Break the Ice Lunar Challenge*.
Retrieved from www.nasa.gov.
[40] Williams, D. R. (2012). Ice on the Moon-A Summary of Clementine and Lunar Prospector Results. *NASA Goddard Space Flight Center. December*.
[41] Zwierzyński, A. J., Ciążela, J., Boroń, P., & Binkowska, W. (2023). Lunar Cold Microtraps as Future Source of Raw Materials—Business and Technological Perspective. *Applied Sciences*, *13*(24), 13030.
[42] European Space Agency. (2023). *ESA invites space firms to create lunar services*. Retrieved from www.esa.int.
[43] *Built for the Moon and beyond*. Retrieved from www.crescentspace.com.
[44] *Lunar terrain vehicles* (2021). Retrieved from lockheedmartin.com.
[45] *Lunar exploration*. Retrieved from/www.lpi.usra.edu.
[46] Soderman et al., (2020). *Scale of Lunar South Polar Mountains*. Retrieved from www.nasa.gov.
[47] Fiore, F., & Elvis, M. (2025). *Space science & the space economy*. *arXiv prepriarXiv:2502.20922*.
[48] Fiore, F., & Elvis, M. (2025). *Space science & the space economy*. *arXiv preprint arXiv:2502.20922*.
[49] Coppus, B., Fisekovic, M., Passon, T., Pujanek, M., & Verweij, I. (2025). *Lunar Ice Extraction Methods*.