

Overview of NASA’s Break the Ice Lunar Challenge Phase 1

Naveen Vetcha¹

Jacobs Space Exploration Group/NASA Marshall Space Flight Center, Huntsville, AL, 35812 USA

Monsi Roman²

NASA Marshall Space Flight Center, Huntsville, AL, 35812 USA

Michael R. Fiske³

Jacobs Space Exploration Group/NASA Marshall Space Flight Center, Huntsville, AL, 35812 USA

Peter Carrato⁴

Bechtel Global Corporation, Reston, VA, 20190 USA

Kurt W. Leucht⁵

NASA Kennedy Space Center, FL, 32899 USA

Tracie J. Prater⁶

NASA Marshall Space Flight Center, Huntsville, AL, 35812 USA

As NASA works to extend human exploration of the solar system, a sustained presence on the Moon will be critical for developing and testing the technologies and systems needed for future missions to Mars and beyond. In situ resource utilization (ISRU)—the use of lunar materials for life support, fuel, energy, manufacturing, and construction—is necessary to limit the delivery of supplies from Earth. One of the most important of these resources is water. Water supports all life on Earth and will be critical to supporting human exploration beyond Earth. On the Moon, water is trapped in icy regolith at the lunar poles, including inside permanently dark and cold craters. Novel approaches are needed to excavate the icy regolith and transport it for processing in support of permanent human missions on the Moon. To accelerate the development of such approaches and to seek diverse ideas, NASA’s Centennial Challenges launched the Break the Ice Lunar Challenge in November 2020. Phase 1 of the challenge was focused on stimulating innovative approaches for excavating icy regolith and delivering water in extreme lunar environmental conditions. The challenge sought to incentivize solutions for maximizing water delivery while minimizing energy use and the mass of equipment required to be transported to the lunar surface. Submissions for phase 1 of the

¹ Challenge Manager, MSFC-ST21, AIAA Associate Fellow.

² Commercial LEO Destinations Utilization Integration Lead, MSFC.

³ Challenge Subject Matter Expert, MSFC-ST23.

⁴ Challenge Subject Matter Expert, Bechtel Fellow Emeritus.

⁵ Challenge Subject Matter Expert, KSC-NEXS0.

⁶ Challenge Subject Matter Expert, MSFC-HP40, AIAA Senior Member.

challenge were due in June 2021 and winners were announced in August 2021. This paper provides details about the execution of the challenge, solutions received, criteria used to select winning solutions, and status of the phase 2 of the challenge.

I. Introduction

As NASA works to extend human exploration of the solar system, a sustained presence on the Moon will be critical for developing and testing the technologies and systems needed for future missions to Mars and beyond. In situ resource utilization (ISRU)—the development of lunar materials for life support, fuel, energy, manufacturing, and construction—is necessary to limit the delivery of supplies from Earth. One of the most important of these resources is water. Water supports all life on Earth and will be critical to supporting human exploration beyond Earth. On the Moon, water is trapped in icy regolith at the lunar poles, including inside permanently dark and cold craters. Development of technologies for Excavation, Manufacturing, and Construction (EMC) on the Moon is a must for making the sustainable presence on the Moon possible. EMC activities on the Moon require a complex process chain from raw materials (in situ resources) to finished product. NASA has conducted significant work in planetary excavation and construction over the last two decades including some open innovation challenges [1]. In 2019, NASA began exploring how the Centennial Challenges Program (CCP) could complement other ongoing efforts across NASA in developing and maturing excavation and transportation technologies that can operate in the extreme environmental conditions that exist at lunar south pole. CCP was established in 2003 to conduct prize competitions to support NASA’s exploration goals [2]. It was inspired by other successful prizes and challenges, including the 1919 Orteig prize for the first nonstop aircraft flight between New York and Paris won by Charles Lindberg [3] and the \$10 million Ansari XPRIZE, which sought to lower the risk and cost of going to space by incentivizing the creation of a reliable, reusable, privately financed, crewed spaceship [4]. CCP seeks innovative solutions to technical problems that can drive progress in aerospace technology and be of value to NASA’s missions in space operations, science, exploration, and aeronautics. The program encourages the participation of independent teams, individual inventors, student groups, private companies of all sizes, and competitors from diverse backgrounds. Since its inception, CCP has successfully launched and operated 22 challenges.

II. Break the Ice Lunar Challenge

In 2019 and early 2020, CCP in conjunction with subject matter experts from the NASA Kennedy Space Center and Frangione + Associates Innovation Advisors, a contractor with expertise in designing and operating open innovation challenges, explored focus areas and potential technical requirements for a challenge to address excavation and transportation technologies that can operate in the extreme environmental conditions of the lunar south pole. Phase 1 of the Break the Ice Lunar Challenge was launched on November 18, 2020. This challenge seeks to incentivize innovative approaches for excavating icy regolith and delivering water in extreme lunar environments. In phase 1, system architecture that maximizes water delivery while minimizing energy use and the mass of equipment required to be transported to the lunar surface were encouraged. Phase 1 mission scenario and the deliverables are described in Ref. [1].

A. Phase 1 Submissions

Phase 1 of the challenge required teams to design high level system architectures. The challenge was open to both U.S. and international teams. A total of 31 eligible teams submitted innovative system architectures capable of excavating and transporting icy-regolith along with extracted water over long distances and in extreme lunar environmental conditions. Teams came from U.S (28 teams), Australia (1 team), Canada (1 team), and Sri Lanka (1 team). Teams came from a diversity of states across U.S (see Fig. 1). Seven states had multiple teams participating: California (5 teams), Arizona (3 teams), Colorado (2 teams), Florida (2 teams), New York (2 teams), South Dakota (2 teams), and Texas (2 teams). Teams came from academia (32% or 10 teams), industry (29% or 9 teams), and group of individual inventors (39% or 12 teams).

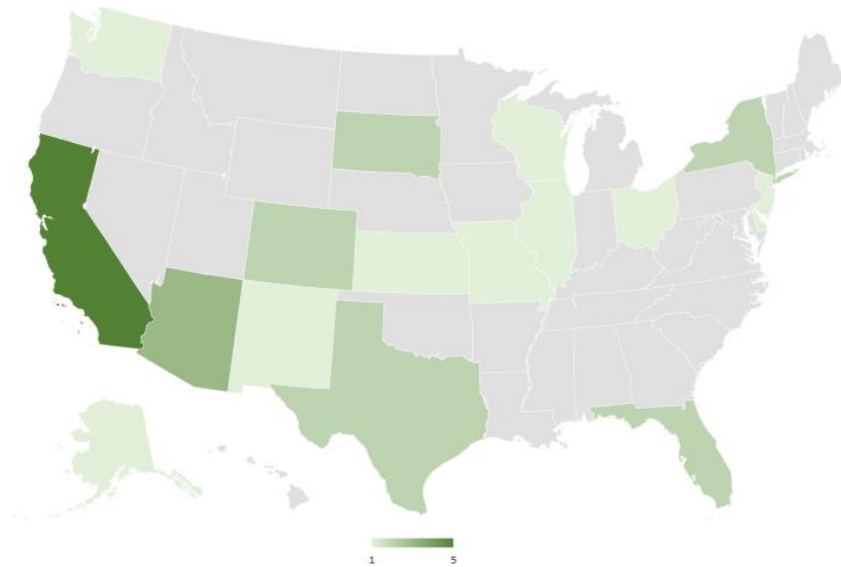


Fig. 1 Geographic distribution of U.S teams in the Break the Ice Lunar Challenge Phase 1

The challenge rules gave 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.

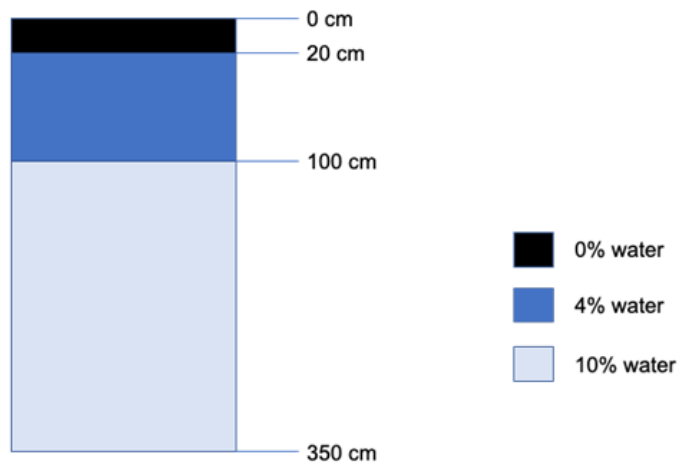


Fig. 2 Percentage of Water in Icy Regolith at various depths.

Competing teams were required to calculate the energy required to collect water based on their chosen architecture design and based on 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.

Many of the submitted architecture designs included creative and innovative plans for preparation of the lunar site before starting operations. 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 proposed 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. Competing teams designed and submitted a wide variety of innovative icy-regolith excavation architectures. Ground contacting 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 adding ultrasonic energy or vibratory action to their ground contacting implements to assist with the excavation process.

One architecture proposed using short bursts from a small onboard liquid-fueled rocket engine to blast vertical holes deep into the surface and force water bearing materials up into a capture volume. And several of the competing teams proposed architectures that didn't actually dig beneath the surface. A few teams proposed heating of the surface using microwave energy or the warm side of a refrigeration circuit in order to sublimate water vapor from the soil. And one team proposed creating an array of vertical drill holes and then inserting heating rods to melt the ice and evaporate the resulting water.

The Challenge rules allowed the 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. A couple of the competing teams proposed cable driven transportation systems. One proposal was a ground dragging cable transportation system and one was an aerial flying cable transportation system.

Several competing teams chose to bring their own icy-regolith processing solutions, though. In these cases, each team had to estimate the landed mass, flow rate limitations, and power utilization of their proposed processing system. A few teams proposed utilizing a sorting or beneficiation process rather than heat to separate the water from the soil, citing a significant energy savings. Proposed beneficiation processes included vibratory, acoustical, pneumatic, electrostatic, magnetic, or a combination of those technologies.

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 had explain 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. Teams who chose to accept the sublimation losses had to estimate, report, and account for the amount of those losses.

Several teams used orbital elevation data to plan and map winding paths which maintained drive slopes below 10 degrees. Multiple teams proposed flinging the frozen water-ice ballistically to take advantage of the lack of atmosphere and the reduced gravity of the Moon. These ballistic transportation proposals also had the benefit of not repeatedly disturbing the dusty soil between the two sites. One team chose to pump liquid water via a pipeline that their architecture installed at the beginning of their mission. And another team chose to transport the water in the form of high temperature steam through a piping system which eliminated the need for mechanical pumping.

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 other architectures 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 haulers that only 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 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 architectures. 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.

Several teams proposed running power cables down into the permanently shadowed crater for use in recharging their excavation equipment. A few teams proposed reflecting sunlight or laser light down into the permanently shadowed crater where the excavator equipment operates and can use it for recharging. One team proposed using a radioisotope thermoelectric generator for some of their equipment and another team proposed using a reversible fuel cell paired with a Lithium-ion battery.

Competing teams submitted a few different options for autonomy of their robotic systems. Many teams cited terrestrial mining operations which run continuously and almost fully autonomously. A few teams proposed manual teleoperation of equipment from a nearby habitat or orbiting asset. Finally multiple competing teams proposed placing dry regolith back on top of the mined area at the end of the 365 Earth-day operation in order to preserve the site for future mining operations.

B. Phase 1 Winners

The competing teams in Phase 1 of NASA’s Break the Ice Lunar Challenge were required to submit the following three deliverables for judging:

- System architecture report, up to 25 pages, worth 200 points
- Excavation plan, up to 5 drawing sheets, worth 50 points
- Mission animation video, up to 5 minutes long, worth 50 points

NASA convened a panel of experts to evaluate and score each team based on their solution’s potential performance in extreme conditions to determine the winners. Specific performance goals included maximum water delivery, minimum energy use, and lowest-mass equipment.

On August 18, 2021, NASA announced \$500,000 in awards for 13 winning teams [4]. The winners included a mix of 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.

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

Team	Location	Prize	Award
Redwire Space	Jacksonville, FL	1 st place	\$125,000
Colorado School of Mines	Golden, CO	2 nd place	\$75,000
Austere Engineering	Littleton, CO	3 rd 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

Redwire Space, headquartered in Jacksonville, Florida, won first place and \$125,000 for its proposed two-rover system designed for simplicity and robustness (see Fig. 3).



Fig. 3 Two rover system proposed by Redwire Space.

Redwire's Lunar Regolith Excavator (L-Rex) shown in Figure 4 is inspired by NASA's prototype Regolith Advanced Surface Systems Operations Robot (RASSOR) excavator. It's designed to excavate large amounts of shallow icy regolith by repeatedly scraping thin layers of the lunar surface from the bottom of the permanently shadowed crater.



Fig. 4 Redwire's Lunar Regolith Excavator.

Redwire's versatile, low-mass transportation rover called Lunar Transporter (L-Tran) shown in Figure 5 is a novel multi-function machine designed to transport the excavator from the landing site to the excavation site, to deploy the excavator, to carry and deliver icy-regolith to the processing plant, and to carry and deliver processed ice to the delivery site.



Fig. 5 Redwire's Lunar Transporter.

The gate of the L-Tran dump-bed opens downward and doubles as a ramp for the L-Rex rover. L-Rex excavates using opposing rotating digging drums which double as both ground contacting digging implements and as holding

containers for the excavated material. Once the digging drums are full of icy-regolith, L-Rex drives up into the L-Tran dump-bed and unloads the icy-regolith. Once L-Tran is full of icy-regolith, it transports and delivers the load about 200 meters away to the NASA supplied water extraction plant for processing into water-ice. Once the processing plant has processed enough loads of icy-regolith, L-Tran then takes on a load of water-ice and it transports and delivers that precious resource about 3 kilometers away to the delivery site which is also 0.5 kilometers higher in elevation. The active suspension onboard the L-Tran lunar transporter allows it to navigate over rocks and craters and also allows it to maintain a level dump-bed while driving on sloped terrain.

Colorado School of Mines in Golden Colorado won second place and \$75,000 for its proposed Lunar Ice Digging System, or LIDS (see Fig. 6).



Fig. 6 Lunar Ice Digging System (LIDS) proposed by Colorado School of Mines.

The LIDS team is comprised of students, faculty, and alumni from the Colorado School of Mines Center for Space Resources, which is a unique graduate program dedicated specifically to space resources research and development. The LIDS architecture consists of three separate and unique rovers. An excavator, an icy-regolith hauler, and a water hauler. It also includes a wireless charging system, communications system, navigation system, and various spare parts.

The LIDS excavator (see Fig. 7) includes an electric jackhammer for breaking up the hard icy-regolith along with a front-end loader for scooping up the broken material and dumping it into the bed of the icy-regolith hauler. The electric jackhammer is mounted on a 3 degree-of-freedom manipulator which gives the excavator a reach wider than the vehicle's base.



Fig. 7 LIDS Excavator.

The LIDS icy-regolith hauler (see Fig. 8) transports and delivers loads of icy-regolith about 200 meters away to the NASA supplied water extraction plant for processing into water-ice. The icy-regolith hauler includes a trap-door bottom in the hauling bed which allows all of the material to be easily transferred from the hauler to the processing plant. The hauler simply drives up ramps to the processing plant which line up the hauler's dump bed over the top of the plant's receiving hopper.



Fig. 8 LIDS icy-regolith hauler.

The LIDS water hauler (see Fig. 9) loads processed liquid water from the processing plant and transports and delivers it in liquid form about 3 kilometers away to the delivery site which is also 0.5 kilometers higher in elevation. The water hauler uses navigation reflectors which were originally placed during initial descent to find its way between the processing plant and the delivery site.



Fig. 9 LIDS water hauler.

Both the icy-regolith hauler and the water hauler include robotic arms designed to be used for assembly, maintenance, and repair tasks. All three of these vehicles are planned to be teleoperated from a nearby lunar surface habitat.

Austere Engineering of Littleton, Colorado, won third place and \$50,000 for its Grading and Rotating for Water Located in Excavated Regolith (GROWLER) system (see Fig. 10).



Fig. 10 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, 12 lunar positioning posts, and associated spare parts.

The GROWLER system will first establish a local positioning system that it will use 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.

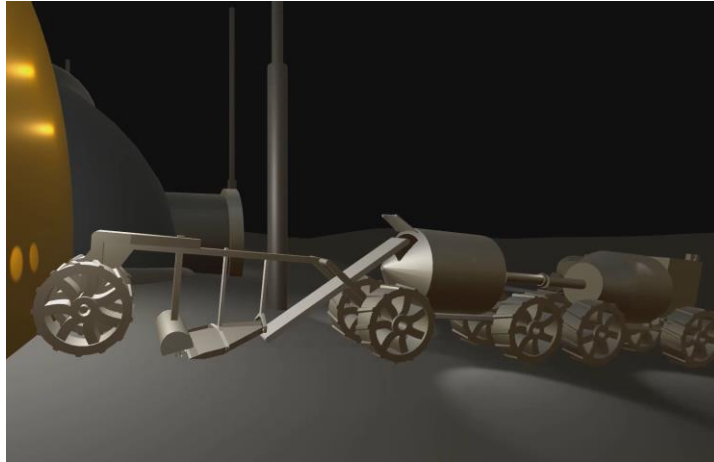


Fig. 11 GROWLER's system performing water transfer operations.

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. In order 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 be rotated 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.

C. Status of Phase 2

On June 2, 2022, NASA launched Phase 2 of the Break the Ice Lunar Challenge [5]. In this phase, NASA is asking teams to design, build, and test an icy regolith excavation system prototype and an icy regolith transportation system prototype to maximize resource delivery while minimizing energy use and the mass of equipment delivered to the lunar surface. Phase 2 will have three rounds of competition (called competition "levels") and up to \$3 million in prizes. Registration for Phase 2 closed on September 30, 2022. Phase 2 was open to U.S. and international teams. Teams were not required to have participated in Phase 1 to compete in Phase 2.

In Phase 2 competition level one, teams will develop detailed engineering designs and long-duration demonstration test plans for their prototype systems. Eligible U.S. teams that meet submission requirements for Phase 2 competition level one will be awarded an equal share of the \$500,000 prize purse. All teams that meet the submission requirements for Phase 2 competition level one will advance to Phase 2 competition level two.

In Phase 2 competition level two, teams will build terrestrial analog full-scale prototypes and conduct durability demonstrations. The top-scoring U.S. team will receive \$300,000; the second-highest scoring U.S. team will receive \$200,000; the third-highest scoring U.S. team will receive \$125,000; and up to five U.S. runners-up will receive \$75,000 each. Up to 15 teams – including winners and runners-up – that exceed the minimum score will advance to Phase 2 competition level three.

In Phase 2 competition level three, teams will test the prototype systems built in Phase 2 competition level two. The top-scoring U.S. team will receive \$1 million, and the second-highest scoring U.S. team will receive \$500,000.

In addition to cash prizes, NASA will also award opportunities to test concepts in a thermal vacuum that will simulate the temperature and atmospheric pressure conditions at the dusty lunar South Pole.

Up to three top-scoring international teams will be recognized as winners in competition level two and competition level three. International teams are not eligible to be awarded prize money or thermal vacuum testing opportunities.

III. Conclusion

NASA's goal of sustainable presence on the Moon needs development of critical technologies that are reliable and can operate for long periods of time in extreme environmental conditions. Phase 1 of the Break the Ice Lunar Challenge received significant number of submissions from academia, industry, and citizen inventors thereby showing the power of prizes and challenges in enabling the development of space technology. Through Phase 2 of this challenge, we hope to identify unique high TRL technologies that will be launched and demonstrated on the Moon in the near future.

Acknowledgments

The authors wish to thank the following individuals for helping with the challenge formulation, development, and execution: John Vickers, Jerry Sanders, Mark Hilburger, Bob Moses, Hari Nayar, Jennifer Edmunson, Jen Bravo, Alisa Ferguson, and Chris Frangione.

References

- [1] Roman, M.C., Vetcha, N., Fiske, M.R., Carrato, P., and Leucht, K.W., "Overview of NASA's Break the Ice Lunar Challenge," *AIAA ASCEND*, 2020.
doi: 10.2514/6.2020-4196
- [2] Davidian, K., "Prizes, Prize Culture, and NASA's Centennial Challenges," *4th International Energy Conversion Engineering Conference and Exhibit (IECEC)*, AIAA 2006-4074, San Diego, CA, 2006.
doi: 10.15394/jaaer.2002.1595
- [3] Charles Lindbergh: An American Aviator. URL: <http://www.charleslindbergh.com/plane/orteig.asp>
- [4] NASA Awards \$500K in Break the Ice Lunar Challenge. URL: <https://www.nasa.gov/feature/nasa-awards-500000-in-break-the-ice-lunar-challenge>
- [5] NASA Opens Second Phase of \$3.5 Million Lunar Excavation Competition. URL: https://www.nasa.gov/directorates/spacetech/centennial_challenges/nasa-opens-second-phase-of-35-million-lunar-excavation-competition.html