Overview and Results from NASA's Break The Ice Lunar Challenge

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Abstract—**NASA's Prizes, Challenges, and Crowdsourcing (PCC) program portfolio is designed to connect the public to the agency's missions. The program encourages creative solutions from a diverse range of solvers which serve to advance the agency's technology development efforts. PCC includes NASA Centennial Challenges, which invites the general public to help close specific NASA technology gaps and incentivizes participation by awarding the Challenge winners large cash prizes for successful outcomes. Centennial Challenges seeks broad participation from independent inventors, companies, nonprofits, small businesses, student groups, and even international entities.**

NASA executed the Break The Ice Lunar Challenge as part of the Centennial Challenges Program between 2020 and 2024. This Challenge focused on advancing technologies capable of (1) excavating tough icy-regolith, or icy Lunar soil, and (2) transporting that excavated material to a different location on the Lunar surface. Phase 1 of NASA's Break The Ice Lunar Challenge required competing teams to conceptualize a high-level system architecture capable of excavating buried icy-regolith and transporting either icy-regolith or processed water several kilometers across the Lunar surface. Phase 2 of the Challenge required competing teams to design, build, and demonstrate robotic technologies capable of excavating simulated icy-regolith material and transporting it across a simulated Lunar landscape.

This paper provides details about the development and execution of the Challenge, the results of each Challenge Phase, and a discussion of the significance of the technology developed under the Challenge for NASA's exploration goals.

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1. INTRODUCTION

NASA is charged with leading the aeronautical and space activities of the United States. As such, NASA has a broad portfolio of work, which includes aeronautics, space operations, science, and space exploration technology development. NASA's Centennial Challenges program [1], which uses prizes and crowdsourcing techniques to incentivize technology development and to engage a diverse population of solvers, is part of NASA's Space Technology Mission Directorate (STMD) [2]. STMD conducts technology development to enable future exploration initiatives, including the agency's Artemis campaign [3]. The Artemis missions will return humans to the Moon and establish a long-term, continuous presence there. STMD also supports development of the lunar economy through partnerships with industry. Centennial Challenges represents one avenue for STMD to engage the public in NASA activities and enable them to directly contribute to NASA's technology maturation efforts.

The NASA Centennial Challenges program began in 2005. In the program's nearly 20-year history, Challenges have focused on a diverse range of topics [4], including spacesuit glove design, 3D printing of habitats [5], space robotics, cube satellites for deep space missions, biological manufacturing, and food production approaches for long duration missions. To date, NASA has executed 22 Centennial Challenges with more than 400 teams participating and has awarded over 20 million dollars in cash prizes. Centennial Challenges actively encourages outside the box thinking and intentionally recruits solvers from outside of the traditional space domain. The diversity of competitors and ideas has resulted in significant advancements and technology maturation over the program's history.

A unique feature of Centennial Challenges is the ability of teams to maintain ownership of the intellectual property they bring to the competition or create under it. Thus, teams are free to commercialize the technology and eventually provide it to NASA as well as other customers. Participants in the Centennial Challenges competition portfolio have gone on to advance their technologies to benefit both Earth and space. Many have launched successful businesses based on the technology they developed for a particular Challenge and received additional government funding to support subsequent technology maturation and mission infusion.

The focus and scope of Challenges in the program portfolio are typically guided by STMD's identified technology gaps/shortfalls, which capture the difference between the current state of the art and the advancements needed to support long duration, exploration class missions such as sustained operations on the lunar surface. STMD released a new list of technology shortfalls in July 2024 [6]. Several of these shortfalls relate to excavation, extraction, processing, and in situ utilization of lunar resources. The ability to collect and use lunar resources is critical to reducing logistical dependencies on Earth and represents one way the Moon can be leveraged to prepare for eventual missions to Mars, where cargo resupply is not an option without a very extended 6 to 9 month time delay.

In the list of technology shortfalls, the following specifically relate to excavation or transportation of lunar regolith:

- Excavation of granular (surface) regolith for in situ resource utilization (ISRU) commodities production. Targets larger scale systems capable of excavating regolith on order of 100,000+ metric tons per year.
- Excavation of hard/compacted icy material. Excavation primarily to support propellant generation (excavation target supports production of 50 metric tons of water, which requires 1000 metric tons of icy regolith).
- Regolith and resource delivery system. Technologies to deliver excavated material from point of excavation to processing facilities are needed for ISRU. Target transportation metric is 1500 km/per year with system lifetime of 5 years.
- Extraction and separation of water from extraterrestrial surface material. This shortfall has a dependency on collection/excavation of icy regolith for acquisition of water from it.
- Extraction and separation of Oxygen from extraterrestrial minerals. This shortfall has a dependency on collection/excavation of regolith for extraction of Oxygen from it.
- Extraction and separation of metals/metalloids from extraterrestrial materials. Before metals which are commonly present in lunar regolith (Aluminum, Silicon, Calcium, Oxygen, Molybdenum, Iron, and Titanium) can be extracted and used in manufacturing or other applications, the regolith containing these metals must first be excavated.

As the shortfall list indicates, there are many useful resources which can be found on the Moon, including water-ice. Multiple lunar missions have proven this to be true, including the 1999 Lunar Prospector mission [7] and the 2009 Lunar Crater Observation and Sensing Satellite (LCROSS) mission [8]. Current evidence suggests that significant quantities of water-ice hide below the surface of the Moon at the poles, especially in deep shadowed craters which rarely see sunlight.

Water on the Moon could be processed into breathing air for our future astronauts or into rocket fuel for future Moon rockets and spacecraft. Figure 1 illustrates the numerous elements and compounds which would characteristically be found in a permanently shadowed lunar crater along with their potential applications. While some might think of the Moon as a static and even geologically dead surface, prior lunar missions have shown that the Moon actually represents a dynamic environment with water, metals, and entrapped gasses that we can extract and harness to reduce dependencies on Earth resources [9].

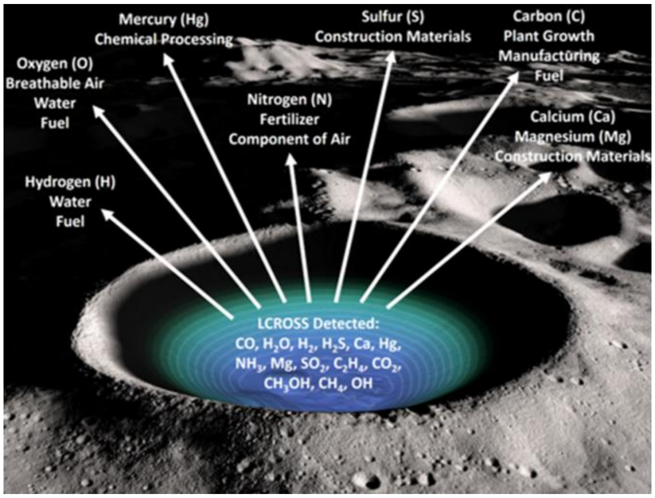

Figure 1. Resources present in icy-regolith and potential uses. Image from Jennifer Edmunson, NASA [10].

Excavation below the lunar surface thus represents a foundational technology for in-situ resource utilization and establishing a sustained lunar presence. It will enable collection, extraction, and use of precious lunar resources to support future human lunar exploration endeavors.

2. BREAK THE ICE LUNAR CHALLENGE (BTILC)

The NASA Centennial Challenges program created the Break The Ice Lunar Challenge (BTILC) in 2020 to address the unique challenges of lunar excavation and to address identified technology gaps [11]. On the surface of Earth, humanity has immense experience excavating and transporting loose granular materials, like sand and dirt, and also excavating and transporting tough solid materials, like bedrock. Both of these use-cases require large, heavy, and tough machinery. But it will be nearly impossible, or at least extremely expensive, to get such large and heavy machinery to the surface of the Moon.

One complexity is the delivery of such systems to the Moon and the subsequent offloading onto the lunar surface. While larger cargo capability landers are in development [12], current payload capacities and volume accommodations for landers are limited. Even once larger capability landers become available, payloads and supporting systems for lunar operations may have a smaller proportion of a lander's mass allocation than major mission elements. Thus, there is a need for new machinery capable of operating on the lunar surface that is also small, lightweight, and energy efficient.

The main goal of the BTILC was to design and demonstrate technologies capable of excavating tough icy-regolith and transporting that excavated material to a different location on the Lunar surface for processing. Competition objectives included excavating large quantities of icy-regolith, delivering large quantities of excavated material, creating hardware and equipment that is lightweight and energy efficient, and demonstrating reliability and durability of the solutions [13]. The Challenge defined "large quantities" as 800 kg of material excavated for every 24 hours of sustained operations. Submitted technologies were scored on excavation rate, transportation rate, total landed mass, total power usage, and the ability to withstand extreme Lunar environmental conditions.

NASA's BTILC was structured in two separate phases. Phase 1 was a conceptual design phase, where teams designed an overall system architecture capable of being landed, deployed, and operated at the Lunar south pole. Phase 2 was a hardware development and testing phase, where teams built actual excavation and transportation robots that were then tested in environments which simulated some of the harsh conditions expected to be found at the operating location.

A publicly accessible Challenge website [14] was utilized to assist with team registration, team communication, and team deliverable submittal.

3. BTILC PHASE 1

Phase 1 Overview

In Phase 1 of NASA's Break The Ice Lunar Challenge [15], teams were given 6 months to create a high-level system architecture design that could land, deploy, and operate at the Lunar south pole. System architecture designs were required to land on the Lunar surface, move mining equipment nearly 4 kilometers to a permanently shadowed crater, excavate icy-regolith, transport excavated material to a local processing plant, and then transport water or ice back to the landing site.

Phase 1 rules [13] encouraged architectures to maximize water delivery and minimize energy use along with minimizing the mass of equipment landed on the Lunar surface. Team deliverables were also scored on scientific & technical merit, design feasibility, and completeness.

Teams were to assume a hypothetical icy-regolith depth profile that defined 4 percent water content beyond 20 centimeters depth plus 10 percent water content beyond 1 meter depth. In the mission scenario, teams were given on-site power plant and on-site power distribution specifications, along with specifications for an optional on-site water extraction plant which could be used in their architecture.

A total of 360 teams expressed interest in competing by registering on the public Challenge website. Of those 360 registered teams, 55 teams submitted the required eligibility documents. 31 teams submitted the required deliverables before the Challenge deadline and were considered for Phase 1 prizes.

Phase 1 Submittals

Submitted 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. One architecture proposed setting up elevated beacons for high resolution local positioning along with ground penetrating radar for detailed mapping of subsurface obstacles. Another proposed placing a rail system on the surface for transportation to minimize dust interaction and to reduce travel times.

Submitted ground contacting digging equipment designs included bucket ladders, bucket drums, grinders, rippers, tillers, augers, coring drills, draglines, hammers, scrapers, and scoops. Most of the proposed architectures operated on relatively level ground at the bottom of a crater, but a few were specially designed to take advantage of the sloping walls of the crater by mining or tunneling directly into them. 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. A few teams proposed heating of the surface using microwave energy or utilizing the warm side of a refrigeration circuit to sublimate water vapor from the soil, thus alleviating the need to dig below the surface. One team proposed creating an array of vertical drill holes and then inserting heating rods to melt the ice and evaporate the resulting water.

Regarding depth of excavation, 74 percent of submittals (23 of 31) targeted the deeper 10 percent water content icy-regolith, even though that material required more energy to access. Only 26 percent of submittals (8 of 31) targeted the shallower 4 percent water content icy-regolith.

Means of getting excavated icy-regolith material from the excavation site to the nearby processing site included a variety of surface rovers containing onboard hoppers or dump beds. Two of the competing teams proposed either surface or aerial cable driven material transfer systems.

Most teams chose to use the Challenge provided processing plant to remove water from excavated icy-regolith. But 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, acoustic, pneumatic, electrostatic, magnetic, or a combination of these technologies.

Teams were required to propose a means of getting processed water or ice from the processing site to the delivery site, which was located nearly 4 kilometers away and included nearly 0.5 kilometers of elevation change. Approaches included a wide variety of innovative transportation architectures. 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. One team chose to pump liquid water via a pipeline which their architecture would install at the beginning of the mission.

The submitted architecture designs included many different creative and innovative robotic work distribution scenarios. Several teams proposed a single flexible and highly capable robot that performed both excavation and transportation. Many teams instead chose to include task-focused robots, with robot(s) dedicated only to excavation or transportation and optimized for each use case. 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 move water specifically from the processing plant to the delivery site.

The distribution of work among robots varied in the competing team's submissions. Some teams chose to operate just one excavator robot, for example, while other teams chose to utilize multiple robots excavating in parallel. Several teams submitted architectures that included special robots and equipment dedicated to initial setup of their architecture. Some even included equipment dedicated to unloading the rovers and equipment remaining on the Lunar lander that had delivered that architecture to the Lunar surface.

Teams were also 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 was operating and using it for recharging that equipment. One team proposed using a radioisotope thermoelectric generator for some of their equipment.

Competing teams submitted a few different options for autonomy of their robotic systems. Many teams cited terrestrial mining operations which run continuously and nearly fully autonomously. A few teams proposed manual teleoperation of equipment from a nearby habitat or an orbiting asset.

As part of their system architecture design, competing teams were required to create a Mission Animation video that detailed their system architecture under operation. Many of the submitted Phase 1 Mission Animation videos [16] can be viewed on the BTILC YouTube Channel [17].

Phase 1 Results

A total of $500,000 in cash prizes were awarded to 13 separate Phase 1 teams based on expert judging of their submitted solutions [18].

Redwire Space (Figure 2), headquartered in Jacksonville, Florida, won first place and $125,000 for its proposed two-robot system designed for both simplicity and robustness. Redwire's lunar excavator robot is inspired by NASA's Regolith Advanced Surface Systems Operations Robot (RASSOR) [19] technology and by NASA's ISRU Pilot Excavator (IPEx) [20] technology.

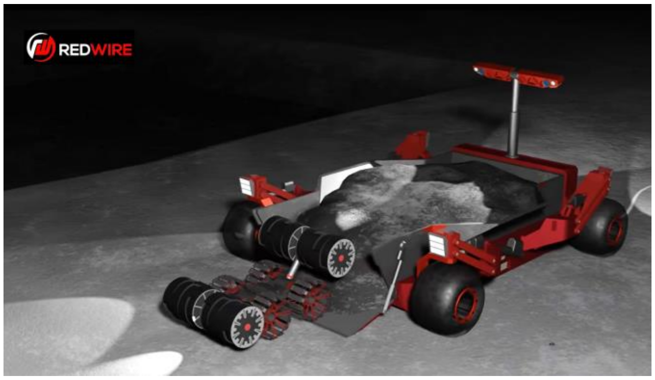

Figure 2. Redwire Space Phase 1 submission. Image from Redwire Space.

Redwire's lunar excavator is designed to excavate large amounts of shallow icy-regolith by repeatedly scraping thin layers of the surface from the bottom of the permanently shadowed crater. Redwire's transportation rover is a novel multi-function machine designed to transport the excavator from the landing site to the excavation site, deploy the excavator, carry and deliver icy-regolith to the processing plant, and carry and deliver processed ice to the delivery site.

Colorado School of Mines (Figure 3) in Golden, Colorado won second place and $75,000 for its proposed three-robot system designed to be small, lightweight, and agile. This architecture consists of an excavator, an icy-regolith hauler, and a water hauler. The excavator 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 icy-regolith hauler transports and delivers loads of icy-regolith about 200 meters away to the NASA supplied water extraction plant for processing into water-ice. The water hauler then loads processed liquid water from the processing plant and transports and delivers it in liquid form nearly 4 kilometers away to the delivery site.

Figure 3. Colorado School of Mines phase 1 submission. Image from Colorado School of Mines.

Austere Engineering (Figure 4) of Littleton, Colorado, won third place and $50,000 for its proposed multi-robot system designed to maximize delivery rates. The architecture includes three identical excavation rovers and two identical ice transportation and maintenance rovers.

Figure 4. Austere Engineering Phase 1 submission. Image from Austere Engineering.

Each excavator rover utilizes an onboard rotary tiller to break up the icy-regolith along with a grading blade to scoop the broken material onto a conveyor system, which moves the icy-regolith material into an onboard rotating extraction drum. An ice transportation and maintenance rover connects to the excavator rover for water transfer operations. In order to make water from the icy-regolith, the excavation rover heats up the rotating extraction drum and pumps the resulting water vapor into the ice transportation and maintenance rover's ice drum. The ice transportation and maintenance rover delivers and deposits the water nearly 4 kilometers away at the delivery site.

As part of Phase 1, ten additional runner-up teams were each awarded $25,000 cash prizes [18]. Runners-up included AA-Star from Redmond, Washington; AggISRU from College Station, Texas; Aurora Robotics from Fairbanks, Alaska; Lunar Lions from New York, New York; LIQUID from Altadena, California; OffWorld Robotics from Pasadena, California; Oshkosh Corporation from Oshkosh, Wisconsin; Rocket-M from Mojave, California; Space Trajectory from Brookings, South Dakota; and Terra Engineering from Gardena, California.

4. BTILC PHASE 2

Phase 2 Overview

Phase 2 of NASA's Break The Ice Lunar Challenge sought to further the development of technologies that could excavate large quantities of icy Lunar regolith and transport excavated material over long distances [21]. Phase 2 required teams to build and demonstrate full sized working physical robots capable of excavating and transporting simulated icy-regolith material. Teams were challenged to excavate and transport 800 kg of material and to transport that excavated material across a distance of 500 meters for every 24 hours of sustained operations. The Phase 2 competition lasted two full years and was subdivided into three separate segments or levels.

Phase 2, Level 1 asked teams to create a detailed design for an icy-regolith excavation and transportation robot or robots. Phase 2, Level 2 required teams to build the robot(s) and demonstrate continuous excavation and transportation operations over a long-term 15 day period at their location. Phase 2 Level 3, or Break The Ice Finals, was an in-person robotic competition with gravity off-loaded excavators and a rugged, granular course to evaluate the transporters.

The Phase 2 rules [21] encouraged teams to maximize icy-regolith excavation and delivery while minimizing energy use. Teams also had to simultaneously minimize the mass of equipment landed on the Lunar surface to perform excavation and transportation functions. In Phase 2, teams were to assume a simplified icy-regolith profile of 4 percent water content at all depths.

5. BTILC PHASE 2, LEVEL 1

In Phase 2, Level 1 of NASA's Break The Ice Lunar Challenge, teams were given 5 months to develop detailed engineering designs for their icy-regolith excavation and transportation robot or robots. Teams could utilize the same robot for both excavation and transportation operations, or they could utilize separate robots for each operation. Parallel approaches, where teams of robots work together to increase system throughput were also acceptable.

One of the required deliverable products for Phase 2, Level 1 was a detailed engineering design for their robot(s). To complete this detailed design, each team had to select robot construction materials, motors, actuators, sensors, batteries, and onboard computers. Teams also had to plan for the construction and assembly of the robot(s) and provide estimates for total mass and anticipated power usage. In addition, teams had to plan for software, communications, and command and control schemes for monitoring and controlling their robot(s).

Another required deliverable product for Phase 2, Level 1 was a detailed test plan which showed how the team would demonstrate future continuous excavation of simulated icy-regolith and transportation operations over a long-term 15 day period. This included details of the icy-regolith simulant the team planned to utilize for long-term excavation, along with plans for a test track to demonstrate long-term and long-distance transportation.

A total of 25 teams submitted the required deliverables before the Challenge deadline and were considered for Phase 2, Level 1 prizes. Prior participation in Phase 1 was not required for teams to compete in Phase 2, Level 1.

Phase 2, Level 1 Submittals

60 percent of submittals (15 of 25) used the same robot for both excavation operations and transportation operations, favoring the benefit of lower total system mass over the disadvantage of increased robot complexity. Only 32 percent of submittals (8 of 25) designed an architecture utilizing multiple identical robots working in parallel to increase overall system productivity or throughput.

Examples of submitted excavator design approaches included the following:

- opposing hollow bucket drums with hardened or titanium scraping blades, inspired by NASA's RASSOR [19] and IPEx [20] robots
- plunging wheels or drums with integrated grinding teeth or cutting picks, inspired by common tree stump grinders
- rotating bucket ladders containing cutting picks, surface milling bits, or scoring cutting blades, followed by scooping buckets or paddles to pick up the loose material
- impact hammers with a single or an array of hardened picks or chisels, inspired by common construction jack-hammers
- chassis-mounted scooping or scraping buckets, inspired by common front-loaders
- arm-mounted scooping or scraping buckets, inspired by common backhoes
- horizontal grinding wheels
- steerable auger cutters
- drills
- percussive motors added to various solutions

Examples of submitted transporter designs included the following:

- 4 wheel designs, 6 wheel designs, track designs
- skid steer designs, front-wheel steerable designs, 4-wheel steerable designs
- rigid suspension and non-compliant wheels, rigid suspension with flexible compliant wheels, rocker-bogie suspension, fully steerable and fully articulated active electronic suspension for all wheels

Examples of unique submitted architecture design features included the following:

- modularity, ability to swap components, and even reuse of major subsystems (like mobility platforms) between robots
- transportation robot charges excavation robot during material transfer, thus allowing nearly continuous excavation operations
- suspension system doubles as a means to lower excavation equipment to, and even below, the surface
- full autonomy of all planned operations
- additional robots dedicated to fixing the excavation and transportation robots or performing battery swapping operations

Phase 2, Level 1 Results

The judges for Phase 2, Level 1 only evaluated team deliverables for compliance or non-compliance with the requirements detailed in the published Phase 2 rules. Teams were given the opportunity to fix non-compliant deliverables and resubmit before the Challenge deadline.

Of the 25 teams that competed in Phase 2, Level 1, 15 teams were determined to be compliant and were granted access to Phase 2, Level 2 of the Challenge [22]. 2 of those 15 compliant teams were international teams which were not eligible for cash prizes; thus, the remaining 13 US teams evenly split a $500,000 Phase 2, Level 1 cash prize purse which granted over $38,000 to each US team.

The 15 winning teams included Aurora Robotics from Fairbanks, Alaska; Cislune Excavators from Alhambra, California; Ice Busters from Olathe, Kansas; Lunar Wombats from Seattle, Washington; Michigan Technological University from Houghton, Michigan; Moog, Inc from Elma, New York; Moon Industry, Inc. from the Netherlands; OffWorld, Inc. from Aldie, Virginia; Redwire Space from Jacksonville, Florida; Space Trajectory from Brookings, South Dakota; Starpath Robotics from Hawthorne, California; Planetoid Mines from Albuquerque, New Mexico; Team Chandra from India; Terra Engineering from Gardena, California; and The Ice Diggers from Golden, Colorado.

6. BTILC PHASE 2, LEVEL 2

In Phase 2, Level 2 of NASA's Break The Ice Lunar Challenge, teams were given 10 months to build their icy-regolith excavation and transportation robot(s) and then perform a long-duration 15 day demonstration test using their robot(s) [21]. Each team was allowed to perform their long-duration demonstration test at a facility or site of their choosing.

During the long-duration test, robot(s) were required to utilize an icy-regolith simulant made from low-strength concrete materials with an unconfined compressive strength of 1.5 to 2.0 MPa. This icy-regolith simulant is essentially structural concrete that's been weakened with soft filler materials, such as ash, extra sand, or other additives. This simulant material was chosen to reduce complexity, cost, and safety concerns which are present with other commonly used regolith simulants. This simulant material approximates the expected strength properties of 4 percent water content Lunar icy-regolith which NASA expects to encounter on the Moon. Additionally, this simulant material is also common in the construction industry and is relatively easy for teams to procure. Choosing this simulant material reduces the barrier to entry for teams entering the Phase 2, Level 2 competition, while still providing NASA with meaningful results and data.

Icy-regolith excavation and transportation robot(s) were required to utilize onboard power systems and wireless communications systems. Systems were not allowed to utilize fundamental physical processes, gasses, fluids, or consumables that would not be able to operate in a Lunar environment. However, electronic and mechanical components were not required to be space qualified nor rated for Lunar environments since they only had to be operated for long periods on Earth as part of the Phase 2 effort. Similarly, working thermal protection systems and onboard lighting systems appropriate for Lunar use were also not required.

During each team's long-duration 15 day demonstration test, the robotic system was required to target excavating and delivering 800 kilograms of material per day for 15 straight days, which totaled 12,000 kilograms, or 12 metric tons. Any material that was hauled by the transporter must have been previously excavated by the excavator. Each delivery cycle had to traverse 500 meters while fully loaded with material and then traverse 500 meters again after material unloading.

Although conducted on Earth, long-duration 15 day demonstration tests were able to simulate some aspects of Lunar surface missions. For example, the 15 day timer was not allowed to pause while the team performed any repair and maintenance activities on their robot(s), including charging of robot batteries. Any spare parts that might be needed during the long-duration test had to be identified, inventoried, weighed, and set aside before the test started. The weight of all spare parts were included in the team's total system landed mass. This was also the case for tools and equipment that might be needed for repair and maintenance during the test.

Within the framework of the rules, if a team needed a sheet of aluminum or a wrench during their 15 day test and they had not previously documented it and set it aside for use, then they had to continue operations without it. This requirement forced teams to think carefully about their architecture design and anticipate what could go wrong during long-duration operations. It also forced teams to minimize tools and spare parts, thereby contending with the logistical constraints imposed by limitations of currently planned Lunar delivery systems such as launch cadence, landed mass, and landed volume.

All teams were required to collect certain data during their long-duration 15 day demonstration test and then include that data in a test report deliverable following test completion. Reported data included the mass of robot(s), spare parts and tools, runtime and energy used by robot(s), distance traversed by robot(s), mass of icy-regolith simulant excavated and delivered, photos of each major piece of equipment, maintenance logs, post-test inspection results, and the icy-regolith simulant recipe.

Of the 15 teams that advanced to compete in Phase 2, Level 2 of the Challenge, 8 teams successfully built and demonstrated their robotic systems before the Challenge deadline and were considered for Phase 2, Level 2 prizes.

Phase 2, Level 2 Submittals

Following their long-duration 15 day demonstration test, each team was required to submit a written test report containing test data along with a time-lapse video showing multiple complete cycles of excavation, transportation, and delivery. BTILC judging staff visited each team's in-progress long-duration 15 day demonstration test to witness testing operations in progress.

87.5 percent of submittals (7 of 8) used the same robot for both excavation operations and transportation operations, favoring the benefit of lower total system mass over the disadvantage of increased robot complexity. Only 12.5 percent of submittals (1 of 8) designed an architecture utilizing multiple identical robots working in parallel to increase overall system productivity or throughput.

Only 25 percent of submittals (2 of 8) were able to meet their goal of 800 kilograms of material excavated and delivered each day for all 15 days.

Demonstrated excavator designs included the following:

- plunging and swinging impact hammer with a single hardened chisel, inspired by common construction jack-hammers
- plunging and swinging bucket wheel with integrated grinding teeth, inspired by common tree stump grinders
- plunging bucket ladder containing surface milling bits followed by scooping buckets to pick up the loose material
- plunging chainsaw style trencher with cutting picks followed by paddles and a conveyor to pick up the loose material
- two teams chose a wide spinning grinding wheel with hardened cutting teeth
    - one chose a scooping bucket to pick up loose material
    - one chose an auger to pick up loose material
- two teams chose opposing hollow bucket drums with hardened scraping blades, inspired by NASA's RASSOR [19] and IPEx [20] robots

Demonstrated transporter designs included the following:

- four teams choose 4-wheel-drive steerable metal wheels
    - three chose all metal tread while one chose mixed metal and rubber tread
    - two chose active electric suspension while the other two chose rigid suspension
- two teams chose 4-wheel-drive non-steerable wheels
    - one chose compliant airless rubber wheels with rubber tread
    - one chose non-compliant metal wheels with metal tread
- 2-wheel-drive non-steerable solid rubber wheels, plus 4 free-spinning casters
- 6-wheel-drive non-steerable plastic wheels with passive rocker-bogie suspension and mixed metal and plastic tread

Unique demonstrated architecture design features included the following:

- additional robots dedicated to performing battery swapping operations
- suspension system doubles as a means to lower excavation equipment to, and even below, the surface
- full autonomy of all test operations

Time-lapse videos [23] of long-duration 15 day demonstration tests which were submitted by many of the Phase 2, Level 2 teams can be viewed on the BTILC YouTube Channel [17].

Phase 2, Level 2 Results

A total of $850,000 in cash prizes were awarded to 6 of the 8 competing Phase 2, Level 2 teams based on expert judging of their submitted solutions [24]. The judging for Phase 2, Level 2 involved evaluating the teams' designs as documented in submitted test reports for mass efficiency, energy efficiency, reliability & durability, and Lunar simulation fidelity.

Starpath Robotics (Figure 5) from Hawthorne, California won first place and $300,000 for their small, lightweight, and energy efficient robot capable of both excavating and transporting icy-regolith simulant. Starpath's robot used a pair of opposing bucket drums for digging. It also used a large onboard lifting hopper for storage and hauling and for dump truck style dumping. This robot also included 4-wheel-drive along with a highly articulated active electric suspension system and independent 4-wheel steering for ease of transportation over rugged terrain.

Terra Engineering (Figure 6) from Gardena California won second place and $200,000 for their robot that used multiple small hardened milling bits to scrape and ultimately fracture the surface in an upward manner once at depth.

Figure 5. Starpath Robotics Phase 2, Level 2 submission. Image from Starpath Robotics.

This robot followed its scraping and fracturing operation with occasional scooping buckets to pick up the loose material and deposit it into an onboard hopper. This hopper off-loaded from beneath the center of the robot similarly to a bottom-dump or belly-dump trailer. This robot included 4-wheel-drive and independent 4-wheel steering, but technical issues reduced it to just rear-wheel steering for most of the long-duration demonstration.

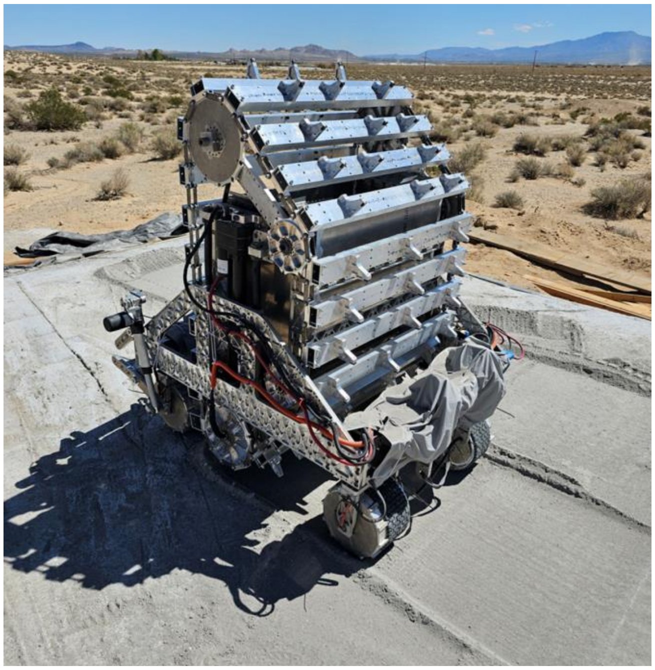

Figure 6. Terra Engineering Phase 2, Level 2 submission. Image from Terra Engineering.

The Ice Diggers (Figure 7) from Golden Colorado won third place and $125,000 for their pair of robots that perform all operations in parallel to increase production rates. The Ice Digger robots use compliant airless rubber tires for grip on all surfaces along with non-steerable wheels to reduce mechanical complexity. Their robots are each dual purpose and include a jack-hammer that can be lowered into the surface for digging, plus a wide front-loading scooping or scraping bucket that holds the excavated material during transportation operations. This robot uses a momentum-driven scooping operation to collect excavated material.

Figure 7. Ice Diggers Phase 2, Level 2 submission. Image from Colorado School of Mines and Lunar Outpost.

In addition, 3 runner-up teams were each awarded $75,000 cash prizes for the performance of their submitted systems [24]. The 3 runner-up teams included Cislune Excavators from Alhambra, California; Space Trajectory from Brookings, South Dakota; and Michigan Technological University from Houghton, Michigan.

All 6 of these finalist teams were invited to Phase 2, Level 3 of the Challenge, or Break The Ice Finals.

7. BTILC PHASE 2, LEVEL 3 OR BREAK THE ICE FINALS

The final 6 teams were given 6 months to prepare for the in-person final portion of the competition which was held in front of a public audience and was also live streamed on the Challenge website [14] [17]. Break The Ice Finals was held in Huntsville, Alabama on the campus of Alabama A&M University in and around their Agribition Center [25].

During Break The Ice Finals, each team competed in both an excavation event and a transportation event. The excavation robots operated indoors on icy-regolith simulant while also being gravity off-loaded to simulate Lunar gravity, or 1/6 Earth's gravity, acting on the robot. The transportation robots, which could be the same robot as the excavation robot, maneuvered and hauled material over complex and rugged outdoor terrain, including rocks, craters, slopes, turns, and loose granular soil. Each team's excavation event was held on the surface of a dedicated icy-regolith simulant slab made from soft concrete materials similar to those used in the earlier 15 day demonstration tests.

Teams were allowed and encouraged, but not required, to make changes to their excavation robots and transportation robots before the start of Break The Ice Finals. This was an opportunity to implement lessons learned from their long-duration 15-day demonstration test. However, changes to their previously submitted robotic system architecture were not permitted. For example, teams could not add a new robot to their system or remove heavy duty components needed to operate in lunar surface environment, but they could make modifications to robot(s) based on lessons learned from long-duration testing provided these changes continued to support a mission scenario of excavating and delivering 800 kg of icy-regolith every 24 hours for 15 days.

In order to allow lessons learned modifications from the long-duration 15 day demonstration tests while also disallowing system architecture changes, a Finals Event Modifications Report deliverable was required to be submitted by all competing teams. This report was required to detail all modifications that were made to the teams' robotic systems since their 15 day test. Challenge judges evaluated robot modifications included in this report which would impact the architecture's ability to support the required mission scenario. The judges also looked for unreported robot modifications during the Break The Ice Finals event. If changes were made that did not support the mission scenario, a penalty would be applied to that team's Break The Ice Finals score.

All 6 teams that were invited to the Break The Ice Finals were able to participate and compete for the grand prize.

Break The Ice Finals Judging

Similar to the other levels of the competition, the Break The Ice Finals Event encouraged Teams to maximize excavation rates and to traverse rugged terrain, while minimizing landed system mass and minimizing energy usage [26].

In the excavation event, shown in Figure 8, teams were required to demonstrate gravity off-loaded excavation into a slab of simulated icy-regolith material for 60 minutes or until their hopper reached its designed payload capacity.

Figure 8. Break The Ice Finals Excavation Event.

The gravity off-load was accomplished during the excavation event by using a boom crane whose hoist tip followed the robot around on the slab and pulled upwards on a spring-loaded constant hanger support device which was set to 5/6 of the robot's weight. With the crane constantly pulling up 5/6 of the robot's weight, only 1/6 of the robot's weight was left to interact with the simulated icy-regolith slab. Use of a constant hanger support device provided the needed gravity off-load forces and also allowed some amount of vertical travel to occur without changing the uplift force.

The scoring for the excavation event favored teams that had maximized the ratio of their excavation rate to their landed system mass. It also favored teams that had maximized the ratio of their excavation rate to their energy utilized. Within the scoring framework, the mass component of the excavation event was weighted higher, at 60%, than the energy component of the excavation event, at 40%.

In the transportation event, shown in Figure 9, teams were given a maximum of 60 minutes to traverse a course with a load of sand corresponding to their robot's designed payload capacity, then return to the start of the course after the load had been emptied. Gravity off-load was not utilized in the transportation event.

Figure 9. Break The Ice Finals Transportation Event.

The transportation course included rugged terrain and minor obstacles which could not be avoided. This included loose granular material including small rocks, turns of approximately 5 meter radius, in-line slopes of approximately 10 degrees, cross-slopes of approximately 4 degrees, boulders that were too large to drive over, and craters that were too large to drive around. The transportation course also included three optional shortcuts consisting of more challenging terrain which teams could optionally traverse. Optional shortcuts included an extreme boulder field of dense angular rocks, an extreme inline slope of approximately 30 degrees, and an extreme cross-slope of approximately 10 degrees. Teams received a scoring bonus for each successful optional shortcut completed, in addition to the possibility of the shortcut reducing their time on the course.

The scoring for the transportation event favored teams that had maximized the ratio of their transportation rate to their landed system mass. It also favored teams that had maximized the ratio of their transportation rate to their energy utilized. Within the scoring framework, the mass component of the transportation event was weighted higher, at 60%, than the energy component of the transportation event, at 40%. Additionally, scoring bonuses were applied for teams that successfully completed optional shortcuts.

The overall scoring for Break The Ice Finals weighted the results of each team's excavation event at 60% and the results of their transportation event at 40%. The weightings assigned to various aspects of the scoring reflect NASA's prioritization of objectives for systems designed under the competition. The scoring rubric can be found in reference [26].

Break The Ice Finals Results

A total of $1.5 Million in cash prizes were up for grabs in the Break The Ice Finals, plus three separate prizes for teams to test robots or subsystems in a NASA dusty thermal vacuum chamber, which simulates the temperatures and atmospheric pressure conditions found at the Lunar south pole.

Table 1 below summarizes the transportation event results.

In the transportation event, Cislune Excavators from Alhambra, California transported 80 kilograms of material with their 461.8 kilogram robot and returned to the starting block in 18 minutes and 58 seconds using 406 Watt-hours of energy. They successfully traversed all 3 of the more challenging shortcuts in both directions. Challenging shortcuts included an extreme inline-slope, an extreme boulder field, and an extreme cross-slope. Video from this event [27] can be viewed on the BTILC YouTube Channel [17].

Space Trajectory from Brookings, South Dakota transported 160 kilograms of material with their 769.0 kilogram robot and returned to the starting block in 21 minutes and 48 seconds using 213.4 Watt-hours of energy. They successfully traversed the cross-slope challenging shortcut in both directions, although they did get a wheel stuck on a rock on their return trip which increased their time on the course. Video from this event [28] can be viewed on the BTILC YouTube Channel.

The Ice Diggers from Golden, Colorado transported 84 kilograms of material with their 447.4 kilogram robot and returned to the starting block in 4 minutes and 9 seconds using 90 Watt-hours of energy. They successfully traversed all 3 of the more challenging shortcuts in both directions. Video from this event [29] can be viewed on the BTILC YouTube Channel.

Starpath Robotics from Hawthorne, California transported 80 kilograms of material with their 253.8 kilogram robot and returned to the starting block in 5 minutes and 54 seconds

Table 2. BTILC Finals Transportation Event Results

Team and Event Video	Robot Mass (kg)	Payload Mass (kg)	Total Time (min:sec)	Energy Used (Wh)
Cislune Excavators from Alhambra, California https://tinyurl.com/nasabtitransport1	461.8	80	18:58	406.0
Space Trajectory from Brookings, South Dakota https://tinyurl.com/nasabtitransport2	769.0	160	21:48	213.4
The Ice Diggers from Golden, Colorado https://tinyurl.com/nasabtitransport3	447.4	84	4:09	90.0
Starpath Robotics from Hawthorne, California https://tinyurl.com/nasabtitransport4	253.8	80	5:54	100.6
Michigan Technological University from Houghton, Michigan https://tinyurl.com/nasabtitransport5	375.5	270	18:00	149.6
Terra Engineering from Gardena, California https://tinyurl.com/nasabtitransport6	325.3	300	13:39	127.0

using 100.6 Watt-hours of energy. They successfully traversed all 3 of the more challenging shortcuts in both directions. Video from this event [30] can be viewed on the BTILC YouTube Channel.

Michigan Technological University from Houghton, Michigan transported 270 kilograms of material with their 375.5 kilogram robot and returned to the starting block in 18 minutes and zero seconds using 149.6 Watt-hours of energy. They successfully traversed the cross-slope challenging shortcut in both directions and the inline-slope challenging shortcut during their return trip. Video from this event [31] can be viewed on the BTILC YouTube Channel.

Terra Engineering from Gardena, California transported 300 kilograms of material with their 325.3 kilogram robot and returned to the starting block in 13 minutes and 39 seconds using 127 Watt-hours of energy. They successfully traversed the inline-slope and cross-slope challenging shortcuts in both directions. Video from this event [32] can be viewed on the BTILC YouTube Channel.

Table 2 below summarizes the excavation event results.

In the excavation event, Space Trajectory from Brookings, South Dakota excavated and collected 10 kilograms of material with their 769.0 kilogram robot in 50 minutes and 40 seconds using 385.8 Watt-hours of energy. Video from this event [33] can be viewed on the BTILC YouTube Channel [17].

The Ice Diggers from Golden, Colorado excavated and collected 28.5 kilograms of material with their 447.4 kilogram robot in 22 minutes and 2 seconds using 310 Watt-hours of energy. Video from this event [34] can be viewed on the BTILC YouTube Channel.

Cislune Excavators from Alhambra, California excavated and collected 65 kilograms of material with their 461.8 kilogram robot in 60 minutes and zero seconds using 375 Watt-hours of energy. Video from this event [35] can be viewed on the BTILC YouTube Channel.

Michigan Technological University from Houghton, Michigan excavated and collected 129 kilograms of material with their 375.5 kilogram robot in 60 minutes and zero

Table 2. BTILC Finals Excavation Event Results

Team and Event Video	Robot Mass (kg)	Collected Mass (kg)	Total Time (min:sec)	Energy Used (Wh)
Space Trajectory from Brookings, South Dakota https://tinyurl.com/nasabtiexcavate1	769.0	10.0	50:40	385.8
The Ice Diggers from Golden, Colorado https://tinyurl.com/nasabtiexcavate2	447.4	28.5	22:02	310.0
Cislune Excavators from Alhambra California https://tinyurl.com/nasabtiexcavate3	461.8	65.0	60:00	375.0
Michigan Technological University from Houghton, Michigan https://tinyurl.com/nasabtiexcavate4	375.5	129.0	60:00	517.9
Starpath Robotics from Hawthorne, California https://tinyurl.com/nasabtiexcavate5	253.8	91.5	32:20	219.0
Terra Engineering from Gardena California https://tinyurl.com/nasabtiexcavate6	325.3	311.6	60:00	250.0

seconds using 517.9 Watt-hours of energy. Video from this event [36] can be viewed on the BTILC YouTube Channel.

Starpath Robotics from Hawthorne, California excavated and collected 91.5 kilograms of material with their 253.8 kilogram robot in 32 minutes and 20 seconds using 219 Watt-hours of energy. Video from this event [37] can be viewed on the BTILC YouTube Channel.

Terra Engineering from Gardena, California excavated and collected 311.6 kilograms of material with their 325.3 kilogram robot in 60 minutes and zero seconds using 250 Watt-hours of energy. Video from this event [38] can be viewed on the BTILC YouTube Channel.

In the end Terra Engineering (Figure 10), a husband and wife team made up of Todd & Valerie Mendenhall, won first place and $1.0 Million, as well as a NASA thermal vacuum chamber test of their robotic technology.

Figure 10. Terra Engineering, Break The Ice Finals first place winner.

Starpath Robotics (Figure 11), a young space tech startup led by Saurav Shroff, won second place and $500,000, as well as a NASA thermal vacuum chamber test of their robotic technology.

Figure 11. Starpath Robotics, Break The Ice Finals second place winner.

The university student team from Michigan Tech (Figure 12), led by Paul van Susante, won a NASA thermal vacuum chamber test of their robotic technology. This is an in-kind prize for use of a NASA facility rather than a monetary prize.

Figure 12. Michigan Tech, Break The Ice Finals thermal vacuum chamber test prize winner. Image from Paul van Susante, Michigan Tech.

Complete competition results are summarized in reference [39].

8. CONCLUSIONS

NASA's Break The Ice Lunar Challenge was highly successful in generating a multiplicity of approaches to icy-regolith excavation and transportation. Scoping the competition to a well-defined mission scenario with specific, quantitative targets based on technology gaps (amount of icy-regolith excavated, transported, and a time constraint) was very effective in ensuring the systems developed under the banner of the competition were tailored to NASA's specific performance needs and anticipated use of excavation technologies to support lunar ISRU.

While there were practical constraints on materials which drove the use of low strength concrete vs. regolith simulant, this material proved very effective as a practical analog for excavation materials in or near a permanently shadowed lunar crater. The Challenge rules bounded the expected material properties for the material mix and teams had to verify their formulation was within these constraints for their long-term demonstration test. This helped to ensure consistency in evaluating performance during that demonstration testing.

The phasing of the competition – conceptual design, build of hardware and demonstration at team's location, and then in-person competition at a NASA-chosen location – was also effective in leading the teams through a stepwise progression of events to mature their systems and evaluate them. The duration and spacing of competition phases allowed teams to evaluate feedback and lessons learned from the prior level and incorporate it into their design and testing to realize efficiencies and improvements.

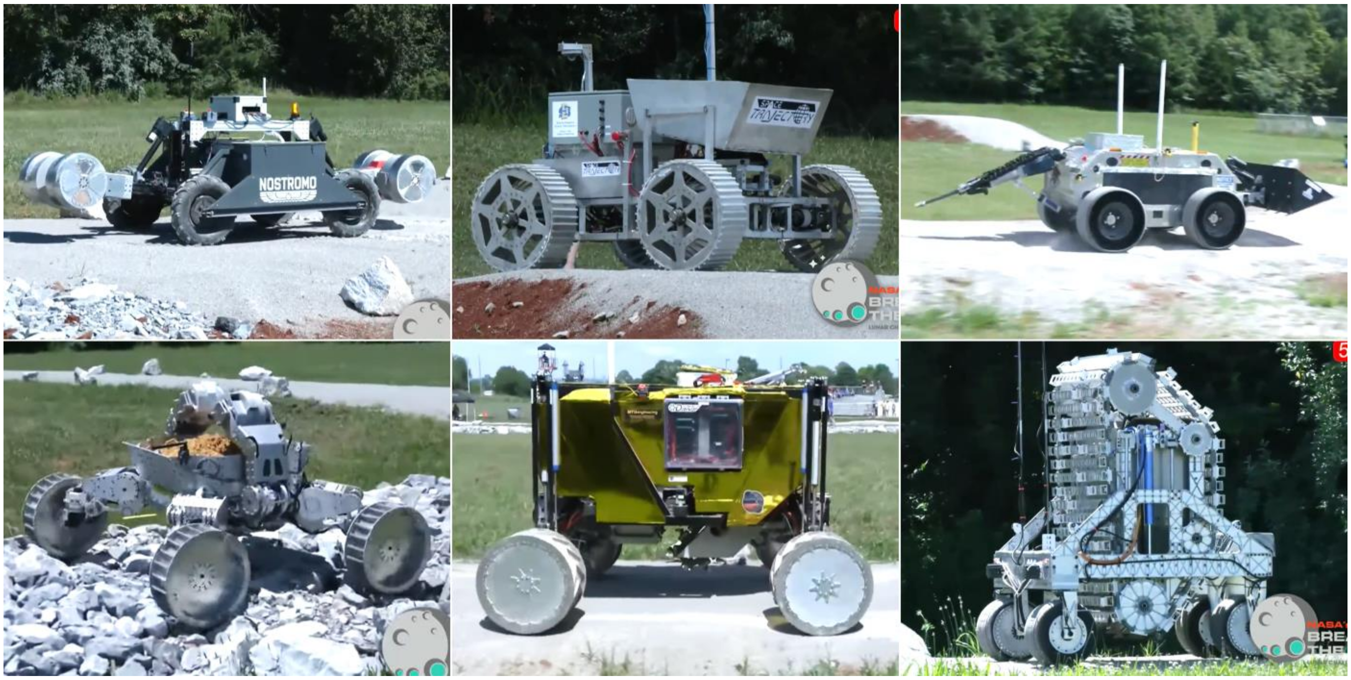

Figure 13. BTILC Finals Transportation Event Robots. From left to right and top to bottom, Cislune Excavators, Space Trajectory, The Ice Diggers, Starpath Robotics, Michigan Technological University, and Terra Engineering.

Figure 14. BTILC Finals Excavation Event Robots. From left to right and top to bottom, Space Trajectory, The Ice Diggers, Cislune Excavators, Michigan Technological University, Starpath Robotics, and Terra Engineering.

The diversity of approaches developed under the competition and discussed in prior sections reflect the multiple technology options available to address STMD's excavation and construction needs. NASA will be able to further evaluate the best-performing excavation technologies through thermal vacuum chamber testing. All teams that participated in the competition are encouraged to continue to pursue engagement with NASA to advance their technology through appropriate mechanisms, including small business innovative research (SBIR) opportunities, cooperative agreements, Space Act Agreements (SAAs), announcements of collaborative opportunities (ACOs), and university research grants.

Historically Centennial Challenges have been highly effective at bringing new entities into the space industry and seeding future partnerships with NASA for technology development. The economic impact of this competition could be highly significant, as opportunities to transport and test payloads on the lunar surface are expected to grow in the coming years through NASA's Commercial Lunar Payload Services (CLPS) program and continued private investment in space missions.

As a foundational technology for the lunar surface, excavation has the potential to grow the lunar economy, enabling establishment of infrastructure and extraction of valuable resources for mission use and return to Earth for scientific analysis. Excavation can also be a critical supporting technology for site preparation and emplacement of assets on the lunar surface.

APPENDIX

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And a huge thank you to all of the teams that took the chance and competed in each Phase and Level of NASA's Break The Ice Lunar Challenge!

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BIOGRAPHY

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