RASC-AL SPECIAL EDITION: MARS ICE CHALLENGE

2017 Challenge Report and Proposed Continuation into 2018

NATIONAL INSTITUTE OF AEROSPACE

REVOLUTIONARY AEROSPACE SYSTEMS CONCEPTS – ACADEMIC LINKAGE

RASC-AL challenges help inform NASA's approaches for future human space exploration and prompt collegiate students to investigate, plan, and analyze space exploration design at differing stages of development. The National Institute of Aerospace (NIA) has managed NASA's Revolutionary Aerospace Systems Concepts – Academic Linkage (RASC-AL) portfolio of premier university-level engineering design competitions since 2009 in close collaboration with NASA sponsors.

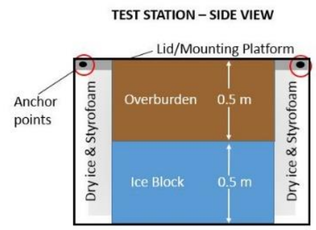
> RASC-AL competitions fuel innovation for aerospace systems concepts, analogs, and technology prototyping by bridging gaps through university engagement.

Periodically, Special Edition RASC-AL programs are established to elicit students' fresh perspective on developing concepts that may provide full or partial solutions to specific design problems and challenges currently facing human space exploration. They have included design-build-test programs for subsystem and component level prototypes, as well as technology demonstrations for critical ISRU capabilities.

2017 RASC-AL SPECIAL EDITION: MARS ICE CHALLENGE OVERVIEW

The Mars Ice Challenge provided undergraduate and graduate students with the opportunity to design and build hardware that could extract water from simulated Martian subsurface ice. Eight teams were chosen through a proposal and down-select process that assessed the teams' concepts and progress throughout the year.

These 8 finalists traveled to the NASA Langley Research Center in Hampton, VA June 13 – 15, 2017 to participate in a multi-day competition where the universities' drilling hardware and software competed to extract the most water from simulated Martian subsurface ice over a two-day period. Each Martian simulated subsurface ice station was comprised of layers, including dirt/overburden and solid blocks of ice. The total simulated subsurface ice depth was ~ 1.0 meter. The drilling and water extraction systems were subject to mass, volume, and power constraints.



Qualifying teams received a $11,200 stipend to facilitate full participation in the competition, including expenses for hardware development, materials, testing equipment, hardware, software and travel to Langley for the competition. Scoring was based on the ability to drill through each layer of the simulated subsurface ice, total water extracted and collected each day, adherence to NASA requirements, a technical paper capturing innovations and design, and a technical poster presentation.

In addition to the test and validation portion of the project, teams presented their drilling concepts in a technical poster session to a judging panel of scientists and engineers from NASA and industry. Poster presentations were based on the team's technical paper that detailed the drill concept's **"path-to-flight"** (how the design can be applied to an actual mission on Mars). Noting the significant differences between Mars and Earth operational environments, this included considerations for temperature differences, power limitations, and atmospheric pressure differences (i.e., challenges from sublimation).

> THE MANDATORY ***PATH-TO-FLIGHT*** DISCUSSION DESCRIBED ESSENTIAL TRADES AND MODIFICATIONS REQUIRED TO OPERATE THEIR SYSTEMS ON MARS.

BACKGROUND/PURPOSE FOR THE MARS ICE CHALLENGE

NASA is embracing new paradigms in exploration that involve expanding our knowledge and leveraging resources as we extend our presence into the solar system. Space pioneering and prospecting towards Earth independence are necessary steps to achieving NASA's goal of extending humanity's reach into space.

Recent discoveries of what are thought to be large ice deposits just under the surface on Mars have Mars mission planners re-thinking how a sustained human presence on Mars could be enabled by a "water rich" environment. Water is essential to enabling a sustained presence, as it could enable agriculture, propellant production, reduce recycling needs for oxygen and provide abundant hydrogen for the development of plastics and other in-situ manufacturing driven materials. Before the water can be used to support sustained human presence, it must be extracted from the Mars ice deposits. Once extracted, water must be isolated to prevent evaporation (or sublimation if still ice) from the low atmospheric pressures and temperatures found on Mars. **The purpose of this challenge is to explore and demonstrate methods to extract water from the Mars ice deposits.**

In the first-known simulated Martian test environment, Mars Ice Challenge participating team members took on the role of astronauts on Mars who monitor and control drilling and water extraction operations. In order to demonstrate a wide range of drilling capabilities of interest to exploration and science, team member interaction with the drill was divided into a period where "hands-on" operation and repairs were permitted and a period where physical "hands-on" crew interaction with the drill was restricted. During all phases of the competition, teams were able to use a control system to "remotely" operate the drill system.

CONNECTING RASC-AL TO LANGLEY'S CENTENNIAL CELEBRATION

The 2017 Mars Ice Challenge was a special edition RASC-AL competition held in conjunction with NASA Langley Research Center's (LaRC's) 100th Anniversary. RASC-AL has served as an integral part of LaRC's talent pipeline as well as an idea mine for many LaRC projects over the span of several decades. As a part of the centennial celebration activities at LaRC, NASA highlighted RASC-AL achievements by hosting a Special Edition Challenge focusing on technology demonstrations for In-Situ Resource Utilization (ISRU) capabilities on Mars, particularly extracting water from simulated Martian subsurface ice. Improving ISRU capabilities will be a focus for NASA over the next few decades, and the **RASC-AL Special Edition: Mars Ice Challenge** offered a unique way for NASA LaRC to recognize RASC-AL's important place in its history while also linking the competition to its future.

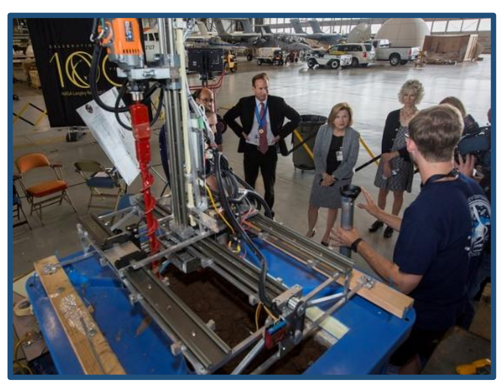
The Mars Ice Challenge was publicized as a flagship Centennial event, and the LaRC community was invited to visit the competition. Hundreds of LaRC employees, contractors, interns, and their families accepted the invitation and interacted with the competitors during the three-day event in the Langley Hangar.

MULTI-MISSION DIRECTORATE FUNDED ACTIVITY

The Mars Ice Challenge received support from various NASA Mission Directorates, each of who see great value in the ability to harvest ice frozen below the surface of Mars. NASA's Space Technology Mission Directorate (STMD) is actively pursuing technologies to enable sustainable human exploration through the use of local resources, exploring concepts to produce fuel, oxygen, and water from the soil and atmosphere of celestial bodies. NASA's Science Mission Directorate (SMD) continues to advance the systems required to produce rocket propellant and other consumables on Mars, as this is of utmost priority to enable productive science missions and extend human activities. NASA's Human Exploration Operations Mission Directorate (HEOMD) works to improve NASA's ability to conduct affordable and sustainable human mission operations beyond Earth, with ISRU capabilities and technologies topping their priority list.

HIGH LEVEL COMPETITION TIMELINE

Late July, 2016	Challenge Launch and Promotion
October 14, 2016	Deadline for NOI (strongly encouraged)
October 20, 2016	Q&A Session for interested teams
Nov. 17, 2016	Deadline for Project Plan Submission
Dec. 9, 2016	Qualifying Teams Announced (Development stipend #1 mailed)
April 2, 2017	Mid-Project Review Deadline
Mid-April, 2017	Stipend #2 sent upon successful completion of mid-project review
May 30, 2017	Final Technical Paper Deadline
June 13–15, '17	2017 Mars Ice Challenge a NASA Langley Research Center



NASA Deputy Administrator, Lesa Roe, talks with competitors

2017 UNIVERSITY TEAMS

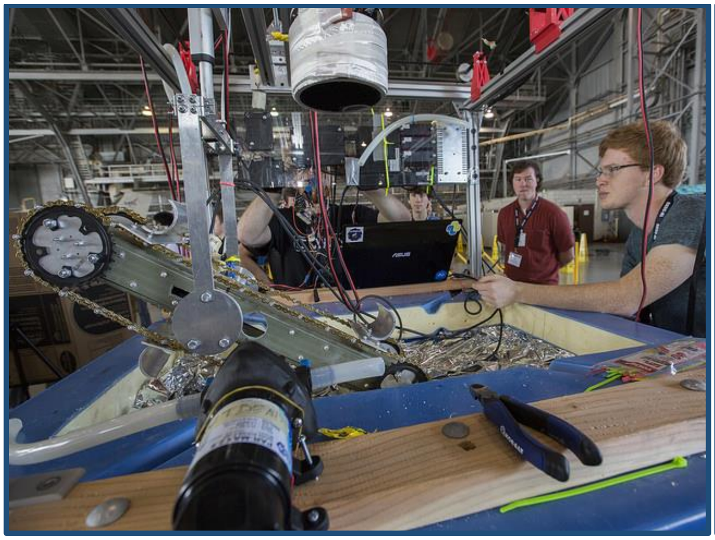
A maximum of 4 students and 1 faculty advisor per team was permitted to attend the onsite portion of the Mars Ice Challenge held at NASA Langley Research Center. However, 109 total students and advisors actively participated in the challenge throughout the year.

West Virginia University
Mountaineer Ice Drilling Automated System (MIDAS)
Advisors – Powsiri Klinkhachorn & Ilkin Bilgesu

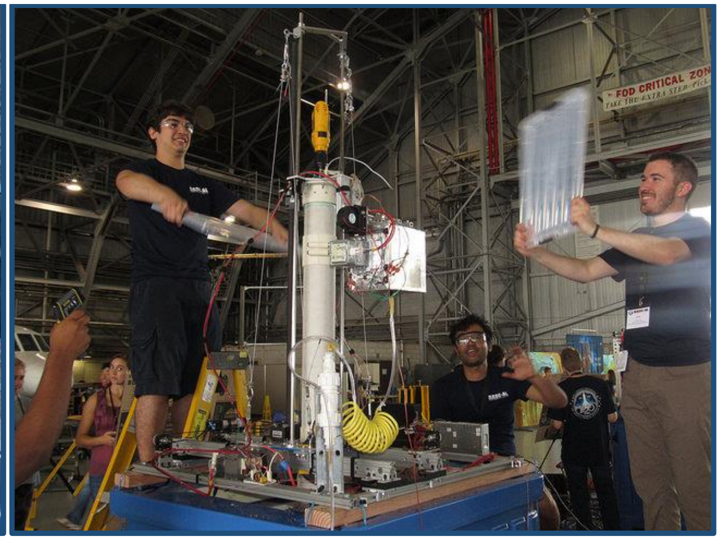
West Virginia University
The In-Situ Resource Extraction System
Advisor – Thomas Evans

Colorado School of Mines
H.G. WELLS (Hidden Ground - Water Extraction Low Load System)
Advisor - Angel Abbud-Madrid

University of Pennsylvania
Mars Water Horizons
Advisor - Graham Wabiszewski



The University of Tennessee, Knoxville
FOLGRS
Advisor - Brett Compton



North Carolina State University
Appetite for Ice
Advisor - Andre Mazzoleni

The University of Texas at Austin
Deepspace Excavator
Advisors - Eric van Oort, Pradeep Ashok, & Mitch Pryor

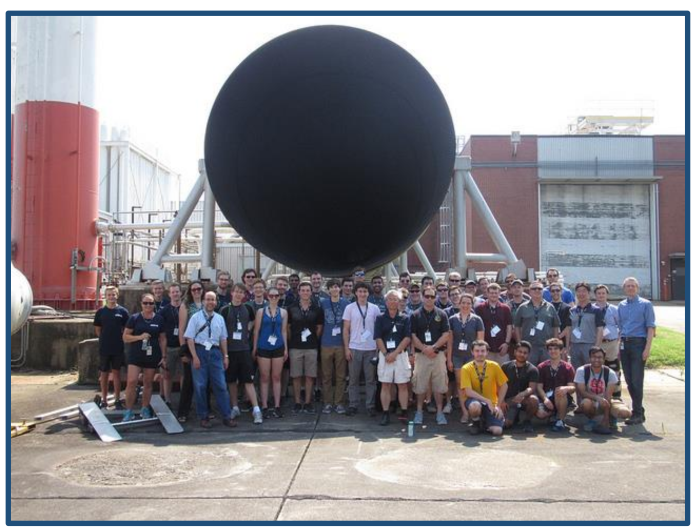
Alfred University
Multi-stage Ice Drilling and Extraction System (MIDaES)
Advisor – Seong-Jin Lee

STEERING COMMITTEE/JUDGES

The 2017 Mars Ice Challenge Steering Committee consisted of:

- Benjamin Galke (NASA Langley Research Center)
- Dr. Anthony Calomino (NASA Langley Research Center)
- Dr. Stephen Hoffman (SAIC/NASA JSC)
- Sharon Jefferies (NASA Langley Research Center)
- Dr. Christopher Jones (NASA Langley Research Center)
- Dr. Robert Moses (NASA Langley Research Center)
- Patrick Troutman (NASA Langley Research Center)
- Dr. Kris Zacny (Honeybee Robotics)

Special guest: Dr. Keith Nicewarner, Mars Surface Robotics Lead, SpaceX



Group photo outside the 8 ft. High Temp Wind Tunnel

COMPETITION RESULTS

1st Place: West Virginia University team MIDAS
2nd Place: Colorado School of Mines
Best Technical Paper: University of Pennsylvania

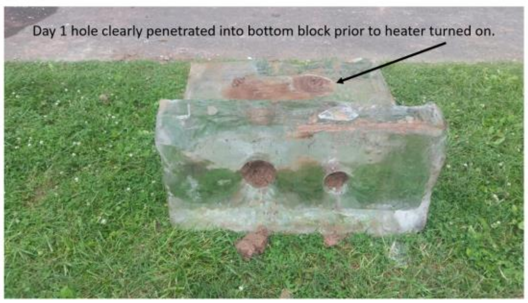
2017 MARS ICE CHALLENGE TECHNICAL PAPERS CAN BE ACCESSED VIA THE ***RASC-AL SHAREFOLDER***

Winning Team – WVU (Midas)

POST COMPETITION ICE STATUS

On Friday morning, the competition test beds were emptied (five days after they were assembled), and the ice blocks were still frozen solid without any standing water at all. There was even some dry ice left in each of the bins! (130 lbs of dry ice was used in each bin – stuffed between the Styrofoam blocks and the wall of the blue containers), demonstrating that the Program Staff and Judges settled on a winning combination of the right amount of dry ice and insulation (Styrofoam bricks, packing peanuts, and overburden). Additionally, the Bonar ice chests had 4 inches of their own insulation in the walls. They out-performed, even in the intense heat (90º+) in the Hangar.

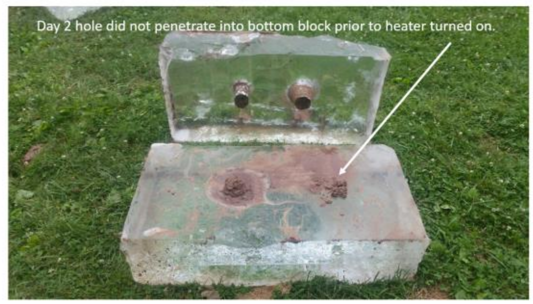
Top Block setting on edge in foreground. Bottom Block setting flat on grass in background.



Day 1 Hole on the right (top view). Extracted 400ml. Day 2 Hole on the left (top view). Extracted far less.

Winning Team – WVU (Midas)

Top Block setting on edge in background. Bottom Block setting flat on grass in foreground



Day 1 Hole on the left. Extracted 400ml. Day 2 Hole on the right. Extracted far less.

Winning Team – WVU (Midas)

Top Block setting flat in foreground. Bottom Block setting flat on grass in background.

Day 1 Hole on the far right (top view). Extracted 10ml. Day 2 Holes, middle and on left. Extracted far less.

2nd Place Team – Colorado School of Mines

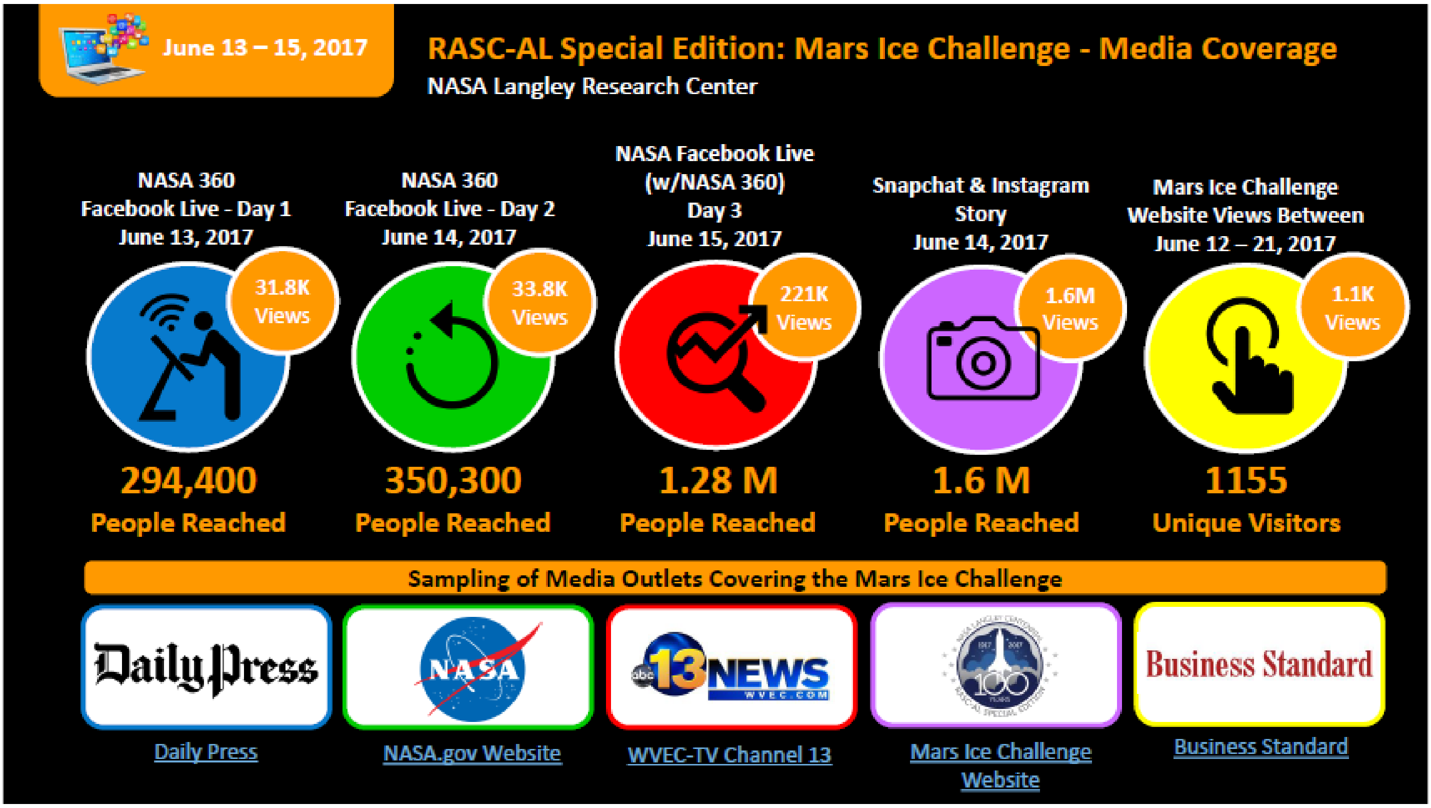
MEDIA COVERAGE OF THE MARS ICE CHALLENGE

The Mars Ice Challenge received a lot of media attention (upwards of 1,000,000 people reached during the FB Live events). Below are links to several of the items posted regarding the Mars Ice Challenge:

- NASA.gov Website
- Daily Press:
- WVEC-TV Channel 13
- NASA 360 - 3 unique Facebook Live events
  - June 13, June 14, June 15
- Business Standard
- NASA YouTube
- Presentation by Guest Speaker, Richard (Rick) Davis
- Presentation by Guest Speaker, Kris Zacny
- Presentation by Guest Speaker, Kevin Kempton
- Various Live Stream captures on the Mars Ice Challenge

MARS ICE CHALLENGE PHOTOS CAN BE ACCESSED VIA THE ***RASC-AL Flickr Account*** AND ***NASA Flickr Account***

Front page story on NASA.gov website



RELEVANCY TO NASA TECHNOLOGY AREAS

DERIVED DIRECTLY FROM *NASA'S 2015 TECHNOLOGY ROADMAP FOR HUMAN EXPLORATION DESTINATION SYSTEMS*

Recent national policy statements have established Mars as the ultimate destination of NASA's human exploration program. In Situ Resource Utilization (ISRU) is a key technology required to enable the affordable establishment of extraterrestrial exploration and operations, by minimizing the materials carried from Earth and by developing advanced, autonomous devises to optimize the benefits of available in-situ resources. Harvesting water from beneath the frozen Martian surface is a critical technology gap needed to benefit both robotic and human missions.

While terrestrial mining and excavation is well developed, the restrictive (time) and non-restrictive (mass, power, autonomy) factors on Earth are not the same for planetary mining. No effort to mine or collect large amounts of solid or gaseous resources has been attempted on the Moon, Mars, or other extraterrestrial bodies. Resource acquisition from hard regolith or rock sources requires drilling or deep digging into regolith consolidated by depth or cold, or both. With strong hydrogen signatures found across wide areas of Mars, NASA has a strong desire to mine for the water frozen below the surface. The key challenge is to minimize or eliminate jamming events. Technologies for high-fidelity modeling of granular flow during collection and transport are needed to design equipment with high efficiencies and low failure rates.

The Mars Ice Challenge is the only competition that uniquely demonstrates mining for water frozen below the surface of Mars.

TA 7: Human Exploration Destination Systems

7.0 Human Exploration Destination Systems Goals: Sustain human presence in space and provide more time for performing core mission activities, while reducing reliance on Earth. All TA 7 goals relate to sustaining human presence in space, which will require existing systems and vehicles to become more independent, incorporate intelligent autonomous operations, and take advantage of the local resources. Advances must be made in finding, extracting, and processing in-situ resources.

Technology Area	Description
7.1 In-Situ Resource Utilization	Leverage in-situ resources to dramatically reduce launch mass and cost of human exploration missions
7.1.2 Resource Acquisition	Extracting, collecting, recycling, pre-processing, and storing targeted "raw" in-situ resources
7.1.3 Processing and Production	Producing, transferring, and storing consumable products, such as water, air, and propellants that are needed by the crew

RELEVANCY TO NASA STRATEGIC GOALS

- **Strategic Goal 1:** Expand the frontiers of knowledge, capability, and opportunity in space, by empowering the NASA community to:
  - **Objective 1.1** Expand human presence into the solar system and to the surface of Mars to advance exploration, science, innovation, benefits to humanity, and international collaboration.
- **Strategic Goal 2:** Advance understanding of Earth and develop technologies to improve the quality of life on our home planet, by engaging our workforce and partners to:
  - **Objective 2.3** Optimize Agency technology investments, foster open innovation, and facilitate technology infusion, ensuring the greatest national benefit.
  - **Objective 2.4** Advance the Nation's STEM education and workforce pipeline by working collaboratively with other agencies to engage students, teachers, and faculty in NASA's missions and unique assets
- **Strategic Goal 3:** Serve the American public and accomplish our Mission by effectively managing our people, technical capabilities, and infrastructure, by working together to:
  - **Objective 3.1** Attract and advance a highly skilled, competent, and diverse workforce

BENEFITS

- The Mars Ice Challenge provides **solutions to a real-world NASA challenges**, through **fresh, innovative concepts and technologies** that will help to expand human presence into the solar system from the top-minds at America's best engineering schools **(Strategic Objective 1.1).**
  - Helps NASA avoid re-inventing the wheel (and, in similar fashion, helps NASA avoid pitfalls made by students in this challenge)
- NASA engineers can leverage the interaction with faculty and students on design problems relevant to NASA to explore workforce pipeline opportunities and attract a highly skilled, competent, and diverse workforce. **(Strategic Objective 3.1).**
  - Provides students with an often first-and-only long-term "cradle-to-grave" project experience
  - The participants are part of a select few who have actual, real experience on this type of ISRU capability – producing a talent pool of qualified students who have unrivaled and invaluable knowledge and experience for the Agency.
- Contributes to the Agency's goals to enhance STEM experience of undergraduate students and provide graduate-trained STEM professionals with basic and applied research expertise. **(Strategic Objective 2.4)**

STEERING COMMITTEE INSIGHTS AND INNOVATIONS GLEANED FROM THE 2017 MARS ICE CHALLENGE

- **Mars is hard:** every team encountered challenges with the regolith, whether in moving through it or having it contaminate their collected water. The **interaction of the regolith with the ice** added a degree of difficulty as compared to only trying to move overburden or acquire pristine ice. As observed in the Phoenix mission, the wet regolith can become sticky, posing a challenge for extraction and separation of water. Teams encountered this same challenge and had mixed success overcoming it.
- **Integrated testing is crucial:** for most of the teams, this was the first time they operated their entire system in an integrated configuration, on an actual testbed. As a result, most teams spent much of their time debugging and modifying their systems rather than drilling for ice. The need for integrated testing is even more applicable when working in the hostile, remote environment of the Mars surface.
- **There is no one right way to get water:** each team brought a different approach to the competition, varying from "conventional" drilling and pumping to ice coring to downhole melting with oil. This diversity provided an **opportunity for NASA and industry to evaluate eight distinct concepts for a relatively small investment**.
- **Relevance to future missions:** water extraction is **critical to a sustained presence on Mars**, as the quantities of propellant and consumables required make delivery from Earth expensive. In addition, there are **similarities between ISRU for Mars and for the Moon** that provide a cross-cutting benefit when examining the systems for acquiring and processing water.
- **Autonomous operations remain a challenge:** the remotely-operated/teleoperated portion of the competition saw little success from any of the teams, with only one team extracting less than two milliliters of water during this phase. None of the teams performed in truly autonomous fashion, as will likely be need for a future Mars mission.
- **Awareness and understanding of the potential of water on Mars:** this competition raised awareness of both the existence of water on Mars, and the ways it can be harnessed. The **teams, visitors, and the public** following along at home all learned about the relevance and importance of the competition, and how it plays into the larger picture of human exploration.

INDIVIDUAL TEAM POST-COMPETITION ANALYSIS IN RESPONSE TO THE FOLLOWING QUESTIONS:

- **Where did you fail and what did you learn from it?**
- **What changes would you make to improve your system next year - and why?**

Alfred University

While we were pleased with our progress given the several set-backs encountered during our time at Langley, we ended the competition approximately 2 inches short of reaching the ice layer. Our outer drill motor became disabled and as such we were limited to utilizing only the inner drill to approach the ice layer. This in turn exposed our inner drill shaft to the overburden and compromised the integrity of the heating coils. To prevent these issues from occurring again it the future, we would recommend making the following improvements to our system:

First, we determined the need to better utilize gear ratios would be paramount for the drilling process. Unfortunately, during the competition, one of our drill motors was worked to the point of failure. Had we created a mechanical advantage with gear ratios, we believe our motors would not have needed to be worked as hard to drill through the overburden, ultimately saving the motor as well as lowering the power consumption of the system.

Another issue that we encountered was the rapid degradation of select components. It was anticipated that certain parts would wear over time and counter measures were to deal with such issues. What was not anticipated was the speed at which certain components would reach the end of their usable lives. One measure to help abate these issues would be to conduct endurance testing to determine which components are best able to run for long durations of time, as opposed to the stop and start testing that we had initially conducted. From these tests, any necessary modifications to parts can be made to improve their longevity.

The biggest change that we would recommend to the system is the overall system process itself. While a multi-drill system is appealing on paper, it was found to be more cumbersome and a pain in practice for several reasons. The first reason was due to our manufacturing capabilities; the tolerances that were required to make this system function as was intended were not attainable with the equipment that we had. Had we been able to access more precise means of machining, such as with CNC machines, we believe the system would have worked closer to the modeled version. Second, the amount of energy required to extract a cylindrical volume of overburden with a multi-drill system ended up being greater than anticipated. This was a testing issue, as we had been testing with topsoil native to Western New York, as opposed the water saturated clay used at Langley. Our power system would need to be revamped to accommodate for this. Lastly, the materials that we chose could have been better optimized to suit the needs of the project, such as using composite vertical and horizontal supports the have improved strength and rigidity, while saving weight.

Our electrical system could have been more organized and systemized. We tried to optimize and minimize the system for efficiency, but experienced some heat issues.

Finally, we would recommend using a coring process as opposed to a multi-drill process to save on complexity, as well as weight, requiring approximately half of the materials used when compared to our original system.

Takeaways: Through this experience we learned that drilling on Mars will be no easy task. To better our design for the future, we would look to recruit a wider variety of engineers. Our team was comprised of fifteen mechanical engineering students, all with similar technical backgrounds. Having a variety of engineers is critical, especially during the design process as different disciplines bring both varying expertise based on their specialization, as well as a different perspective on design. Additionally, we found that the feedback given to us from other types of engineers during the competition proved to be incredibly helpful and allowed us to see things that had previously gone unobserved. Our greatest takeaway from the competition though was learning just how critical the testing phase is, and how thorough it needs to be in order to reach a finished product. When we organized our testing, it was conducted systemically to test each of our systems individually, and every time each system worked seamlessly without flaw. However, prior to the competition, multiple systems tests had not been conducted, and that is when we found several flaws with our system. Ultimately a variety of tests, as well as pushing the system through more rigorous testing would have helped immensely with the competition.

We would like to take this time to thank everyone from the NIA, NASA, and supporting agencies for allowing us this wonderful experience. The lessons learned from our time competing in the RASC-AL Mars Ice Challenge have helped us to become better engineers and will stay with us for a lifetime. Thank you all, and we look forward to the possibility of competing again in the near future.

Colorado School of Mines

We segregated the team into subsystem groups. This was helpful in terms of subsystem "deliverable" accountability, but the groups became too focused on their individual tasks and sometimes forgot to see the big picture. This resulted in work that often created problems for other subsystem groups. Looking back, we should have stressed more cross-subsystem group communication, early and often.

We also spent too much time anticipating results with pen and paper rather than buying the tools and testing our assumptions. We learned to test early and often.

There were a couple of test parameters that we misunderstood heading into the competition. This was our fault. Most significant, was an increase in distance from our platform to the ice surface top. This reduced the length our drill could reach, and therefore the ice we could collect per hole. This forced us to change our strategy from fewer deep holes, to more shallow holes which resulted in additional non-productive casing setting time. The purpose of the casing was to provide a medium for which the cuttings could ascend the auger flutes while also segregating them from the overburden lying above the ice. However, overnight NASA surrounded the ice beds with "dry ice" which dropped the clay temperature lower than we were expecting. This resulted in a harder to penetrate material which significantly slowed our casing setting times.

Next year, we would try to bring an additional computer science and electrical engineering student onto the project. The electrical/computer science interfacing was unquestionably our biggest challenge. This being said, not having students in these areas forced the rest of us to spend time learning these disciplines. When we started, we were struggling to turn on an LCD. It's empowering to realize that in the end we created a robot that could drill autonomously for 12 hours.

Having to purchase expensive materials really forced us to understand what it was we were buying. It was truly an authentic form of education, one that is difficult to experience in "textbook academics".

Next year, we would decrease the diameter of our bit. Both testing and Mechanical Specific Energy data suggested a 2 inch bit was too big. The increased "bit face" required more energy to penetrate the ice and the increase in hole volume did not pay off. We would also change the angle and material of our auger flutes. They were not optimized for lifting cuttings (we found this out too late in the design process).

In conclusion, we'd like to thank you SO much for providing what was truly an exceptional experience. Not only during the June competition, but also during the 10 months preceding, in which we were forced to develop engineering skills that are not typically taught in academics. Colonizing Mars is a tremendous challenge. To spend a week surrounded by people who have spent their lives pursuing such an ambitious scientific endeavor was inspiring. Our team was completely humbled by the level of attention that went into making the competition what it was. It is something we will remember for the rest of our lives.

North Carolina University

Design improvements:
Motor Cooling & Torque: A motor should be selected with sufficient torque for the bladed auger selected, for the 4 inch auger used more than 300 in-lb is needed if the overburden is near liquid/mud conditions. The ice & overburden must be at design temperature (-0 - -40C) during all stages of extraction for proper functioning of a bladed-shrouded-auger design as friction with the sidewalls can cause overheating. Less torque would be needed if there is less friction between overburden and shroud walls.

The mission-ready motor must be suited for sustained loads without overheating, single body aluminum construction with phase exchange heat pipes is recommended, and additive aluminum manufacturing methods would be very useful.

Screw drive would be better for positioning than belt drive if 3 axis positing is desired, weight would be a consideration.

Competition wise, a simpler design (1 axis) may have worked better, but for flight ready hardware we still think 3 axis control would be a huge advantage to serviceability (less frequent trips to drill site to move the drill).

Future designs should make use of as many tension structures as possible using guy wires, they provide dampening against vibration modes as well as adding stiffness when operating at maximum height.

A single body construction, consisting of the fluted auger, pilot bit, and auger blades, would be recommended to achieve a custom flute separation distance.

Custom, single body construction of the force-on-bit to auger mount would provide more reliable force on bit construction.

Competition Improvements:
We recommend that experiment test beds should take place in a freezer to prevent any unpredicted temperature gradients between the ice and overburden; it is also critical that the overburden contain the proper amount of water per soil mixture, as any deviation in water concentration can have a large effect on drill performance, and the test overburden soil/water mixture should be as close as possible to the conditions that will be experienced by the rig at a proposed Mars landing site.

University of Pennsylvania

Our system consisted of several subsystems that were tested separately in order to ensure that they could operate effectively. However, our team had significant challenges with system integrations because although each subcomponent was meticulously designed and prototyped, we did not leave ourselves enough time to bring all the pieces together and test as an integrated system. We learned to not underestimate the complexity of or the amount of time required for final system integration.

Additionally, our drill motor stalled many times while excavating through the overburden during the competition. We were only able to find a limited number of equations related to drilling through clay or ice. Because of this, we were unable to accurately calculate the required torque and power for our drill with much certainty. We learned to rely on experimental information more heavily when theoretical information is limited.

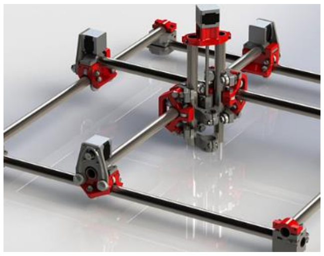
If we were to redesign our system for next year, we would stick with our actuated core drill design, but we would focus on reducing overall weight and increasing the rigidity of the actuation system. In order to reduce weight, we would use a smaller diameter core drill. A smaller drill not only removes weight from the drill itself, but also removes weight from the actuation system needed to move it. We originally chose a large diameter drill because we thought the rate of penetration of the drill would be quite low and we wanted to maximize the amount of ice we obtained from each hole. However, rate of penetration ended up being higher than we predicted, thus reducing the need for a large diameter core drill. To further reduce weight, we would likely attempt to design a melting system that could melt the ice within the drill. This would remove the need for the melting chamber, thus reducing the weight and complexity of our overall system.

The other main focus would be improving the rigidity of the core drill actuation system. Our system experienced significant oscillations when the drill was powered on; this greatly decreased the positional accuracy of the drill. Additionally, our system was beginning to shake itself apart by the end of the competition. We believe the fundamental actuation concepts (lead screws for X and Y axes and Rigibelt for Z axis) have the potential to work, but much more secure guide carriages are needed for the rails. Ideally, we would use a guide carriage that completely wraps around the guide rail. We believe roller coasters would be a good source of inspiration for this.

University of Tennessee, Knoxville

The biggest problem with our device was our trencher. As such, most improvements would focus on making the trencher effective. As we have probably mentioned already, our team had next to no robotics experience entering the first phases of design. Now that the team is more experienced, the time and money spent solving relatively fundamental problems last year can be leveraged into a much more thorough design phase for potentially problematic elements, like the trencher.

The chassis from 2017 model of our device placed the attachment of each tool head at the highest point in the possible working space. This caused the trencher to produce a significant moment on the linear actuator to which it was attached. The first and most fundamental change would be to change the frame so that XY translation was handled as close to the test bed as possible, similar to how a modern CNC machine works. The image below demonstrates what I mean, with the horizon plane of the chassis as low to the test bed as possible. ***(Image credit to ASME)***



This would significantly shorten the moment arm the trencher applied to the chassis, making it much easier to implement a two-point attachment system for the trencher, so that the linear actuator doesn't bear the shear caused by the trenching moment. This would allow us to re-design the trencher to make it more robust when dealing with compacted or wet overburden. Most industrial scale trenchers (used for strip mining) use very low profile cutting teeth to grind through soil and rock, and account for the lower volume extraction per revolution by spinning very quickly. These units are also typically cylindrical instead of oblong, reducing their weight. The lighter, more robust chassis and reduction in weight spent on trencher size would allow us to implement a more robust trencher with a larger, high-torque motor (with a gearbox) and steel or ceramic-tipped teeth instead of buckets, to prevent wear. Overall, this type of trencher, like the industrial trenchers by which it was inspired, would be suited to dig through both cohesive (wet) and hard-packed (frozen) overburden. Other improvements, such as procuring shorter linear actuators, redesigning the filtration system to prevent overflow, and re-organizing wiring, would also be made to "clean up" the design.

Takeaways: Members of our team learned technical skills like CAD, Python, 3D printing, and Machining. Our programming and electronics team had to learn all the skills required to wire and control the robot from an external laptop. Our team had to learn how to design drive systems and components based on available parts. The competition was also an opportunity for team members to build technical writing skills, time management skills, in some cases leaderships skills. Members of the team also had to learn how to mathematically develop a model for a system, identify the limits and assumptions of that model based on applied boundary conditions, and defend those choices with evidence from relevant scientific literature. Team members also learned how to use computational methods to analyze systems, both in the aforementioned models and physical systems on the prototype. Members also built organization, communication, and financial management skills.

Additionally, our team gained practical robotics knowledge. For instance, our team learned basic things like the different types of shaft collars and the advantages and disadvantages of each. Our team learned, broadly speaking, what parts are commercially available and which must be custom made, and how modify commercially available components and minimize machining to construct parts which would otherwise be prohibitively expensive. Our team learned what can and can't be done on the different hardware available to us through the university, and what level of precision can be expected from each, as well as learning what level of precision is required for different components. Our team also learned the importance of, and techniques to design for maintainability and ease of repair.

Specific to problems which arose at the competition, our team gained insight into planning for a competition setting. Our team is now much more aware of the types of failures that typically happen during long demonstrations and can design around those issues (overheating, wear on motors and electronics, etc.) Our team also now understands the importance of "over-engineering" critical design elements so that they still function correctly in sub-optimal or unexpected operating conditions.

University of Texas, Austin

One thing in particular we learned about is the importance of testing. During our rig tests, we burned out all three of our heating coils and so we had to scramble before the competition for a solution. If we had tested sooner we would have had an easier time dealing with this problem.

Based on the results of this year's competition, here are a few things we would change about our system:

- Use a coated heating coil rather than uncoated for superior durability
- Spade type bit design instead of the wood cutting bit type we used
- Bars on the bit to prevent mud from collecting around the casing.
- Add a bottom hole temperature sensor to ensure the casing doesn't get too hot when heating.

Additionally, we would consider removal of the outer casing. Our design utilized an outer casing to prevent collapse of the wellbore, but this year's test bed was firm enough to hold up without the casing. The removal of the casing will allow our team to shrink the size of the bit dramatically and increase the Rate Of Penetration, ROP.

When the casing is removed, the heater (which was previously located on the casing) will need to be rethought. Some of the NASA engineers mentioned that on the rovers on Mars are powered by nuclear reactors that don't easily produce electricity. They mentioned that a design which heated with a thermal fluid would be superior than a design that used an electric heater. As such, our thoughts are to go with a design that pumps a hit brine down the stem of the drill bit.

West Virginia University (The In-Situ Resource Extraction System, Advisor: Evans)

Lessons Learned:

- The drill bit's length beyond the auger stem should be minimized in order to facilitate the conveying of regolith cuttings up the drill stem.
- The drill needs to cut approximately 3 inches into the ice in order to minimize any excess contamination of the meltwater by regolith mud.

Points of Failure:

- A pump was incorrectly connected and was not identified until operations began. Additionally, two valves malfunctioned for no apparent reason.
- A second pump stopped working towards the end of the competition. The cause of this failure was not assessed. A higher quality pump would have most likely avoided the issue.
- In general, we did not take full advantage of our available amperage. We used only 2.5 of an allotted 10 A. Additionally, our self-assembled drill motor only operated as a rotary drill. As a result, we did not utilize our WOB as efficiently as we would have had a rotary percussive motor been used.

Improvements:

- A new rotary percussive drill motor will be selected that provides more cutting power to the bit and conveys regolith without stalling.
- An injection system that uses a hotter fluid will facilitate the extraction of far more water.
- The drill bit will be modified into a cutting strip of tungsten carbide welded to the bottom of the auger to facilitate conveying operations.
- As an alternative to the injection system, a single heat probe could be lowered into the borehole after it has been drilled and melt the ice. We could then extract the meltwater through a system similar to our current extraction system configuration.

West Virginia University (MIDAS, Advisor: Klinkhachorn) – Winning Team

First and foremost, we learned the overburden is much harder to deal with than we anticipated. We thought even though it was loosely packed, when it was chilled in the container with the dry ice, it may become relatively firm. We also thought since there was so much overburden, the weight of it all would probably pack the soil tightly but leave the crust somewhat crumbly. We discovered it was pretty loose overall and prone to collapsing. A weight on bit didn't even register when drilling through the testbed, except when we hit the ice. In the future we would use a deployable casing wall in unison with our drilling system to prevent major collapses.

Another lesson learned was the method of liquefying ice in the bore hole is much better when the heater assembly is used as a melting probe. By this we mean on day one we drilled to target depth and then deployed the heater in the ice. On day two we drilled to the ice layer and let the heater melt its way through as it was gradually translated down to target depth. The first method required very high heat because it utilized heat radiation to melt ice until water made contact with the heat sink, which was terribly inefficient. We also didn't have a way to sense when there was water, so we did boil off some water with the high heat. The second method on day two utilized the principles of heating by conduction and convection, which melted a lot more ice and led to a very large overburden collapse. Obviously heating through conduction and convection is more efficient, but it was one of those things we didn't think to try until we got there.

A lesson learned about the heating method itself was that we required a high wattage heater of shorter length. This would have prevented a lot of problems with overburden collapses. As the shorter heater melts its way down, it will eventually sink much farther below the ice-overburden interface. If most of the melting process is done further down, a cavity in the ice will form that will create a ceiling to hold the overburden. Also extracting water while melting down through would be beneficial to prevent continued melting of the ceiling while translating the heater downwards. A sensor for water level feedback would be great to integrate into the extraction assembly for the future.

VERBATIM PARTICIPANT QUOTES (FACULTY AND STUDENTS)

- I liked the **hands-on aspect** of the project. Most projects at my school offered little hands-on experience.
- My participation in the Challenge was invaluable! **I have never learned so much from one project in such a short amount of time.** It was a very difficult task, but I think it gave a great real-world view of taking a project from the very beginning of brainstorming ideas all the way to building and showcasing the system. I am more motivated than ever to work in aerospace.
- I loved the **networking opportunities**! It was really awesome getting to interact with so many people as they came by our stations. I also really enjoyed being in the hangar (despite the heat). Being surrounded by such greatness was a big motivator.
- I enjoyed **talking with the industry professionals about their approach to the problems** – it was quite fun!
- I loved this experience as a whole. This is one of the first competitions I've ever been in and it was such a great learning experience. All of the issues we had with our robot may have discouraged some, but **I really embraced it as a chance to solve problems and be a real engineer**. The networking was great, too!
- **This competition invigorated me with new life and inspiration**. Prior to the competition, I was seriously contemplating moving out of engineering and into another field because I felt burned out. This competition helped reignite my love of space and ISRU technology and motivated me to begin pursuing employment opportunities in those areas.
- In addition to developing people skills, we also got a large **insight into rapid prototyping**. It is great to build intuition for problem solving in real world applications. We learned about how design is more than just ideas on a page. You can draw whatever you want but if you don't have a way to manufacture or bind the materials together than it doesn't do you much good.
- This competition was very educational, an excellent networking opportunity, and the **opportunity to work on a real, challenging problem.**

- The overall values in participating (in the Mars Ice Challenge) include: learning how to work as a team and **understanding the complexities of projects in the real-world.** Many of our students had no industry experience and this will help them learn how to bridge the gap between academia and industry.
- The amount of experience I gained from fixing our robot so many times and getting hands on design work is amazing. **Seeing a project from cradle to grave** is something I don't think a lot of people in the industry see.
- There is great value participating in the RASC-AL Mars Ice Challenge. The chance to compete and apply your skills is a great way to **realize what your strengths and weaknesses are**.
- The Mars Ice Challenge **gave me passion for future projects**. Even though my team was ultimately unsuccessful in gathering ice, it made me want it more. It made me want to come back next year and demonstrate how much we have learned.
- This challenge was a very involved, hands-on experience. It was my **first exposure to ISRU problems and potential solutions**. It affirmed my goal to work in the space industry – and provided affirmation that the industry has a clear path forward.
- The **networking was perhaps the most valuable** part. Discussing with the professionals about how to tackle a challenge opens up new possibilities for other competitions.
- The **presentations are really informative and provide insight on what NASA is doing**. The tours themselves are worth coming to rascal for. Also we have a chance to show off all of our hard work.
- The competition was a great learning experience in general. **Planning, organization, teamwork, communication and all aspects of engineering were involved** in getting ready to compete.
- There are three things I liked best about this competition:
  - Association with one of the premier research institutes on earth.
  - Career opportunities in research
  - Definitely **motivated me to be part of the research to send humans to Mars**.

VERBATIM LESSONS LEARNED FROM THE PARTICIPANTS (ANNONYMOUS)

- This challenge really showed me the **importance of planning projects out completely and documenting every step**. It also showed how important testing is.
- Always have a **pre-flight check of every system component** before you test. **Never underestimate a single testing condition either**. Prepare for an even fight every time.
- Testing is the most important part of this competition and **more iterations of testing** allow for smoother operations.
- I would have tried to **manage time a little better and to have identified big problems earlier in the process**. Hindsight is always 20/20, but I know I personally as well as my team as a whole would have been much less down to the wire if we had simply addressed issues more quickly. Also, I learned **the value of asking meaningful questions**. It was crucial that I fully understood what I was asking as well as the person's response when trying to solve a problem.
- I would've made a **smaller coring drill** which would've lighten several components of the system and expedited the drilling process. Also, if I were to do this again, I would put **more emphasis on the testing of the system** in order to give ourselves more testing time prior to the competition.
- **Innumerable lessons about project management, team dynamics**, etc.
- I would have tried to **have a full working 3d model and simulations by the end of January** to begin building from. I would also spend the budget in a better manner, buying more expensive higher quality parts from the beginning. We were not used to handling such a large budget.
- Would rework certain design elements, **consult excavation expert during early phases of design**
- 1. Always test entire system before competition begins. 2. **Establish a clear chain of command during operations** to prevent confusion by the operator. 3. **Don't reinvent the wheel**; if someone makes a good drill incorporate it into your design instead of designing your own.
- We would definitely have **focused on developing our controls system first to make it more reliable and robust**. Additionally, the building process allowed us to identify which designs worked and which did not. We would obviously try now to skip to the final design and improve upon its operation. Finally, we would probably incorporate a different drill motor since we initially thought that we were supposed to create our own rather than incorporate pre-existing drills into a final design.
- **Smaller heating element, smaller drill** (the overburden was not nearly as hard as we believed it was going to be), then a **case wall to help prevent collapsing.**
- **Trencher needs a big redesign**. When Kris said scoops were no good in his presentation I thought "well let's see how this goes" and I wasn't really surprised from the outcome. We needed **more torque** and i would prefer a smaller device, maybe even make it circular like some trencher devices in the industry
- Two things that I learned were that a smaller drill would have been sufficient as well as a smaller heater. Also a different system should be devised to measure the weight on bit.
- More testing. It helps to **test early to work out the bugs**.
- Several lessons learned:
  - **Change the auger drill diameter from 4" to 2".** This would significantly reduce the drilling motor torque required as well as the overall weight (~ 8 Kgs).
  - **Improve the X-Y motion guide-rod and carriage** for a smoother operation.
  - **Make the MW chamber smaller**, more compact.
  - Make most **parts from aluminum/space ready components** like the auger shroud.

PARTICIPANT IDEAS FOR IMPROVING FUTURE COMPETITIONS

- Maybe **extend the competition a day** so that the process is a little less rushed? Not sure if that's logistically possible, but perhaps a full day for networking/poster session etc. rather than a couple hours.

- It would be awesome to **design a system that could capture CO2 from the atmosphere on Mars and use it for plant growth**! This could be nicely coupled with an evolved water extraction competition...since plants need that too!
- **Water seems like the most important ISRU problem to solve**, plus the availability of water vs other resources (like minerals or ores) make larger-scale competition more feasible. I would see how much it would cost to build something like a hockey rink, then make one big test bed for each team to share. Devices would be limited to initial weight and volume at the beginning of the extraction session, but would be allowed to expand beyond that volume during competition (allowing for "fold-up" robots). Devices could be mobile or stationary. That would be a better simulation of a Martian environment, but might be more expensive and require more involved devices.
- The Mars ice challenge version 2 should be held and **the 2017 challenge technical papers should be shared with newly selected team along with pictures of the actual system, so that they do not have to re-invent the wheel.** This next version as per me would have even more sophisticated drilling systems. Also the hands-on could be made wireless for more realistic and challenging simulation along with in vacuum testing.
- Since the RMC competition is getting a little dry a potential could be for **a combination of the two (RMC and Mars Ice Challenge).** A robot needs to drive down to an area, extract water (in what ever form the team deems best) then return it to a storage bin/tank.
- I would have liked **more time to operate the r**obot just because it would give us more time to work out any bugs and harvest more water.
- The Martian regolith was rather thawed by the time we started drilling. **By pouring dry ice over the top of the soil 1-2 days prior to the competition, the soil might reach a lower temperature.**
- I would like to **focus more on projects like this that have direct applications to near-future events**, as opposed to something like "Develop an energy-harvesting array for the Moon that beams solar energy back to Earth as microwaves".
- **More time to set up and test the first day.**
- I remember seeing a report that researchers are testing 3D printing with simulated lunar dust. It'd be cool to maybe do something with Mars. Honestly, **I would love to take our robot and improve it for another competition like this.**
- Weight On Bit (WOB) requirement seems a little excessive. I'd think that as long as you're not lifting the rover, **WOB should be limitless.**
- I believe it would be interesting to have a **box that sits over a hole and collects and condenses the sublimated ice and delivers the water drops to a bottle or some other collection device.**
- I liked this competition and I think that it is **vital in future missions and definitely worth pursuing.**

PROPOSED 2018 MARS ICE CHALLENGE

Due to the overwhelming success of the 2017 Mars Ice Challenge, NIA proposes to re-invigorate the Mars Ice Challenge in FY18 with evolutionary updates and enhancements that **directly align with NASA's Technology Area (TA) 7 for Human Exploration Destination Systems.**

In support of NASA's objectives to achieve advancements in technology related to human space exploration, NIA proposes to administer this prestigious collegiate-level design challenge once again in FY18 and will seek **innovative and creative engineering ideas and design concepts** from the university community for **water harvesting systems** from simulated Martian subsurface ice stations.

FY18 UPDATES AND ENHANCEMENTS

The second Mars Ice Challenge will be managed with improvements based on lessons learned that will increase the ability of the teams to succeed. For instance, the 2017 challenge technical papers will be shared with newly selected teams (along with pictures of the actual systems) so that new teams will not have to "re-invent the wheel." Through this iterative learning process in proficiencies and capabilities, it is expected that the 2018 competition will yield more sophisticated/successful drilling systems and NASA will be able to glean more innovation from the water extraction systems. For university professors, this learning process expands the educational content of the exercise for their design courses.

The Mars Ice Challenge Steering Committee has already begun compiling updates to the design constraints and requirements document, based on lessons learned from the FY17 program that could only have been learned by actually doing the competition one time through. This includes, but is not limited to:

- Requiring teams to do a full integration (with video proof) prior to arriving at NASA
- Providing additional time for teams to set-up their systems on Day One
- Increasing the weight of the score for the technical paper/path-to-flight
- Removing the disqualifications and moving instead to measured penalties (so as not to demotivate students)
- Revamping the weight on bit requirement
- Reducing the water content in the clay to be more representative of a desiccated Mars surface material
- Customizing each mounting platform to the specific needs of each team – on the set up day of the competition.
- Further engaging the ISRU folks at other Centers, such as JSC

New in FY18:

- **Brand new, dedicated RASC-AL Special Edition website**
- **Prizes -** NIA has been invited to give a talk about hosting the Mars Ice Challenge from a programmatic perspective at the next Space Resources Roundtable (SRR) in Golden, Colorado. Additionally, there has been a request for the top winning concepts to present their concepts at the SRR, and a travel stipend is being proposed as the prize for the top two winning teams to attend this event.
- **Potential Industry Support** - NIA has started the process of seeking additional industry support to augment the proposed FY18 Mars Ice Challenge, by bringing additional teams, providing larger development stipends, and/or providing seed funding and opportunities to further develop promising concepts. Tesla has expressed interest in supplying Powerwalls for the drills.

CONCLUSION

The Mars Ice Challenge is a high-caliber program that has made good use of the expertise of both NASA and industry partners, and has demonstrated successful industry-NASA-university collaboration. The basic premise of the program is closely aligned with NASA's strategic goals and technology areas of interest to NASA's STMD, SMD, and HEOMD.

ISRU is a critical capability for sustained human exploration of the cosmos, but at the same time, ISRU on Mars is an unproven capability and cannot be put in the critical path of architecture until proven. Therefore, ISRU (as an end in and of itself) is manifested to take incremental steps toward the desired outcome. The idea of extracting water with regolith is super important, and the Mars Ice Challenge uniquely demonstrates real-world challenges associated with mining the ice frozen under the surface of Mars. It also attracts hundreds of the nation's brightest young engineering students to work on solutions to a critical ISRU technology gap. All participating NASA and industry subject matter experts agree that continuing this program has the potential for a high return on investment and a high likelihood of achieving crucial incremental gains for ISRU water harvesting on Martian surfaces, at a very low cost to NASA.

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