National Aeronautics and Space Administration

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National Aeronautics and Space Administration

NASA's Analog Missions

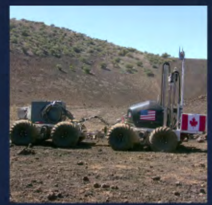
Paving the Way for Space Exploration

Desert Research and Technology Studies (D-RATS)

NASA Extreme Environment Mission Operations (NEEMO)

Haughton-Mars Project (HMP)

Pavilion Lake Research Project (PLRP)



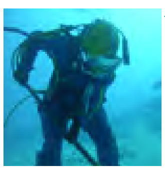
In-Situ Resource Utilization (ISRU)

Inflatable Lunar Habitat Analog Study

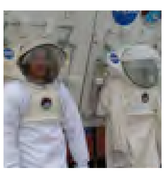
Executive Summary

Today NASA pursues technical innovations and scientific discoveries to advance human exploration of space. To prepare for these complex missions, a vast amount of planning, testing, and technology development must be accomplished. Yet, forecasting how that planning will translate into everyday operations in space is difficult while still on Earth. To help prepare for the real-life challenges of space exploration, NASA relies on Earth-based missions that are similar, or analogous, to space. These are called analog missions—field activities set in remote locations with extreme characteristics that resemble the challenges of a space mission. NASA conducts these missions in extreme environments around the globe to test technologies and systems and to help guide the future direction of human exploration of the solar system. This report profiles NASA's active analog missions, with highlights and successes from the last few years:

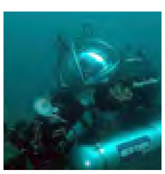
This mission tests roving and extravehicular activity (EVA) operations in an environment that, like the Moon and Mars, features extreme temperatures and difficult terrain. The Desert RATS program conducts an annual three-week exploration mission at Black Point Lava Flow, Arizona, investigating the most effective combination of rovers, habitats, and robotic systems; optimum crew size; effects of communication delays; effectiveness of autonomous operations; and how to improve science return for exploration missions.



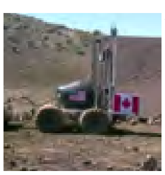
The NEEMO analog mission uses the world's only operating undersea laboratory, *Aquarius*, which is located 62 feet underwater off Key Largo Florida, to mimic the isolation, constrained habitats, harsh environments, and reduced gravity that challenge space exploration missions. The annual two- to three-week missions provide NASA aquanauts an opportunity to train crew; conduct behavioral, physiological, and psychological experiments; test hardware configurations; test exploration operations; and perform a host of other exploration-related activities.



The Haughton Crater, on Devon Island in Canada, resembles the Mars surface in more ways than any other place on Earth, including a Mars-like landscape of dry, unvegetated, rocky terrain; extreme environmental conditions; and an ancient crater. HMP missions advance plans for future exploration of the Moon, Mars, and other planetary bodies by testing technologies and operations and conducting science research in this environment.



Pavilion Lake, British Columbia, Canada is home to rare carbonate structures called microbialites, which are similar to some of the earliest remnants of life on Earth. This analog mission conducts annual scientific research projects to study these structures while also testing science research operations and providing astronaut training to support future human space exploration.



Researchers and engineers at NASA are developing mining equipment and production facilities designed to produce oxygen, water, building materials, and fuel in situ (on the planetary surface). To test these technologies and their operations outside of the lab, the ISRU analog team travels to the dormant volcano, Mauna Kea, in Hawaii. Mauna Kea has a harsh, dusty terrain like the Martian and Lunar surfaces and a high oxygen content, similar to that of the Moon's soil.

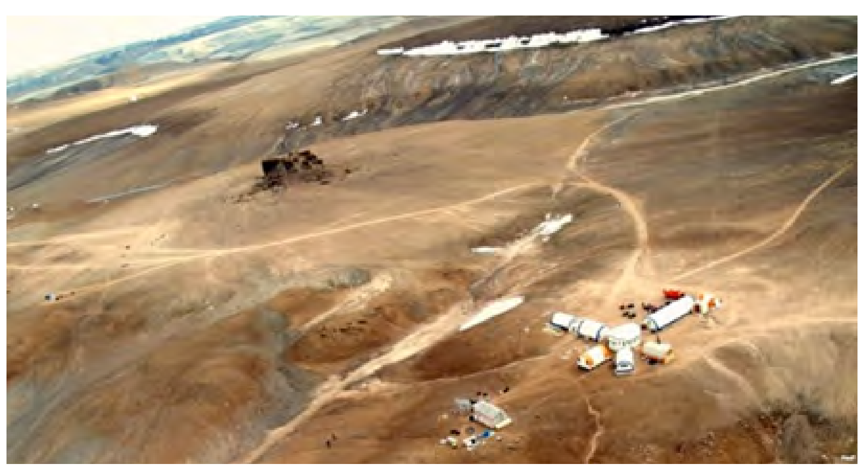
McMurdo Station, Antarctica is an extreme and remote environment, presenting challenges not present in a lab. This analog mission allowed scientists and engineers to test an inflatable habitat for one year in this environment, to gain a new perspective on design and operations for similar habitats that may be designed for space exploration missions.

Analog missions reach out and inspire the public about the possibilities of exploring space.

Paving the Way...

Today NASA pursues technical innovations and scientific discoveries to advance human exploration of space. Space exploration missions are complex and challenging, even more so when human crews are involved. A mission must include technologies and operations that protect humans and hardware from the harsh space environment and provide the best support from ground control and robotic assistants, while enabling productive scientific observations and sampling. To prepare for these missions, a huge amount of planning, testing, and technology development must be done. Yet, forecasting how that planning will translate into everyday operations in space is difficult while still on Earth. To help prepare for the real-life challenges of space exploration, NASA relies on Earth-based missions that emphasize multiple elements as similar, or analogous, to space. These are called analog missions.

*Analog missions provide an opportunity to test operations in constrained living environments, like in the rover of **Desert RATS** 2010.*



*Extreme environments on Earth provide a unique opportunity to test operations for future space exploration missions. Haughton Crater provides an analog for exploring Mars in the **Haughton-Mars Project**.*

An analog mission is a field activity set in a remote location with extreme characteristics that resemble the challenges of a space mission. NASA has used this approach since the Apollo days, when they tested roving, space walking, and research techniques to prepare for Apollo missions in meteor craters and volcanic fields in Arizona and Hawaii. Today, NASA conducts analog missions in extreme environments around the globe to help plan and guide the future direction of human exploration of the solar system.

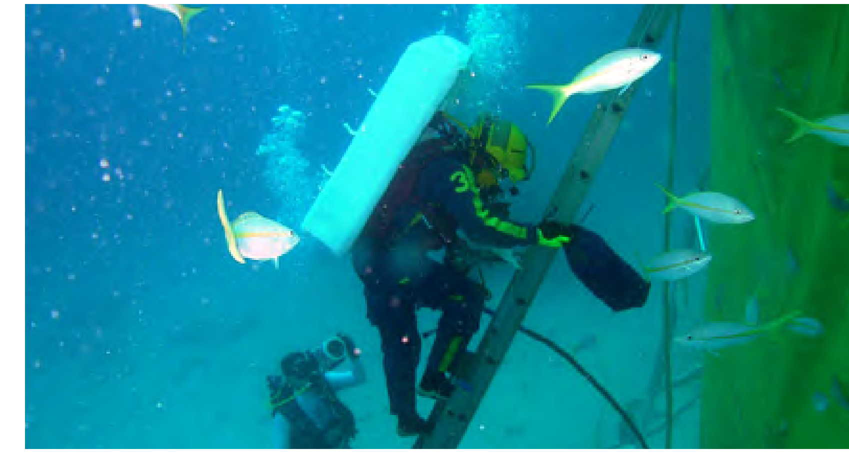
Answering Exploration Questions

Because no one environment on Earth is the same as what we will find when exploring space, NASA uses a portfolio of analog missions to simulate different aspects of space exploration. Example environments include the isolation and confined living spaces of underwater habitats, rugged or cratered terrain similar to the Moon or Mars, sites with soil compositions and textures similar to other planetary bodies, and remote environments that experience extreme temperatures. By simulating space exploration in analogous environments on Earth, NASA is able to test hardware and operations to ensure successful technology development, realistic requirements, and integrated mission operations, reducing the risk and cost of future space missions. NASA's current analog activities are answering key questions for human exploration of the Moon, Mars, near-Earth asteroids (NEAs), and other celestial bodies, by testing technologies in operational environments, simulating day-to-day operations of an exploration mission, and conducting scientific research as it would be done in a space environment.

Many analog studies conduct multiple missions over many years, which allows NASA to develop exploration technologies in an incremental manner. This "build a little, test a little" approach enables NASA to learn more about the operational requirements for exploration missions, while tailoring equipment designs to fit the mission's and crew's needs. The build a little, test a little technique is an iterative process. It starts with a technology prototype that is tested during the mission. Feedback from the testing allows engineers and scientists to develop an improved version of the technology, which can be tested and improved again the following year. This iterative process helps NASA develop technologies with optimized performance and safety capabilities for space exploration systems.

In addition to testing hardware, all the analog missions provide an opportunity to simulate exploration missions to test operations and learn from crew experiences. By testing different operational approaches in analogs, NASA can determine the best combination of systems and humans to complete specific aspects of a mission, such as long-distance space walks (also called extra-vehicular activities or EVAs), scientific research, or build-up of an outpost site. These tests help determine details such as which tasks are best conducted robotically or by astronauts, how communications with ground teams can best support scientific research, and how to design space habitats to be comfortable and productive for the crew. Simulated exploration missions also provide training opportunities for astronauts. For example, in NASA Extreme Environment Mission Operations (NEEMO) missions, crew members can experience the challenges of moving and working in a reduced-gravity environment to prepare themselves for similar challenges in space.

Finally, analog mission participants can test techniques for doing scientific research in space by conducting relevant and valuable science missions of opportunity on Earth. In some cases, science goals are achieved as secondary objectives during the analog mission, such as the human physiology experiments conducted during the NEEMO mission. Alternatively, the analog mission and testing might support a primary science mission, such as the study of freshwater microbialites in Pavilion Lake. In each of these cases, real scientific research is conducted on Earth, while also testing different approaches to optimize the planning, technology, and expectations for conducting scientific research during space exploration missions.

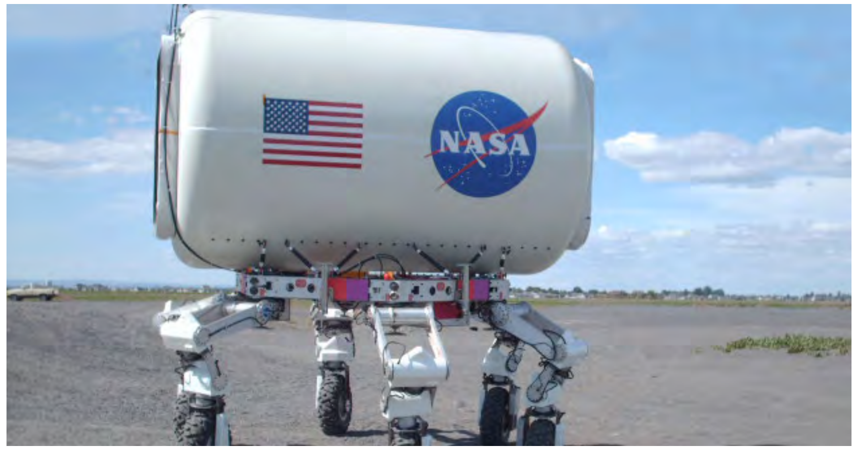


*Performing real mission operations during analog studies provides NASA with a unique opportunity to prepare for exploration on the Moon, Mars, and near-Earth asteroids. An aquanaut on the **NEEMO** mission simulates descending a ladder from a habitat in a simulated low-gravity environment.*

*The harsh environment at analog sites provides an opportunity to test technologies for use in space. The **Inflatable Lunar Habitat Analog Study** was conducted in Antarctica to simulate the extreme cold of space.*

Analog Missions Reach Beyond NASA

Analog missions and the value they provide are not restricted to NASA. Given the relatively low cost of analog missions and accessibility of most analog sites, these missions are an attractive opportunity for corporate, government, and international partners to test their systems and hardware outside the lab. Analogs provide an



The “build a little, test a little” approach allows scientists and engineers to test a technology in a simulated environment, make incremental improvements, and continue testing as technologies are developed for use in space. The ATHLETE rover was tested at ***Moses Lake*** *in 2008.*

Partnering in technology development is likely to be part of any future human exploration of space. Analog missions provide hands-on experience to test technology integration before it launches. The RESOLVE system partners with the Canadian Space Agency in the ***ISRU*** *analog at Mauna Kea.*

opportunity to test technology integration between NASA and partner technologies to ensure everything works seamlessly once it is in space. Working with partners also strengthens relationships, building a true “team spirit” for future missions. For example, the Canadian Space Agency is a major partner of the two analog studies located in Canada, the Haughton-Mars Project and the Pavilion Lake Research Project, and the NEEMO missions are made possible by the use of NOAA’s underwater laboratory. Every analog mission teams with corporate, international, and academic partners. Analogs will continue to attract potential partners who want to contribute to the space program while gaining valuable knowledge, experience, or testing opportunities for their own objectives.

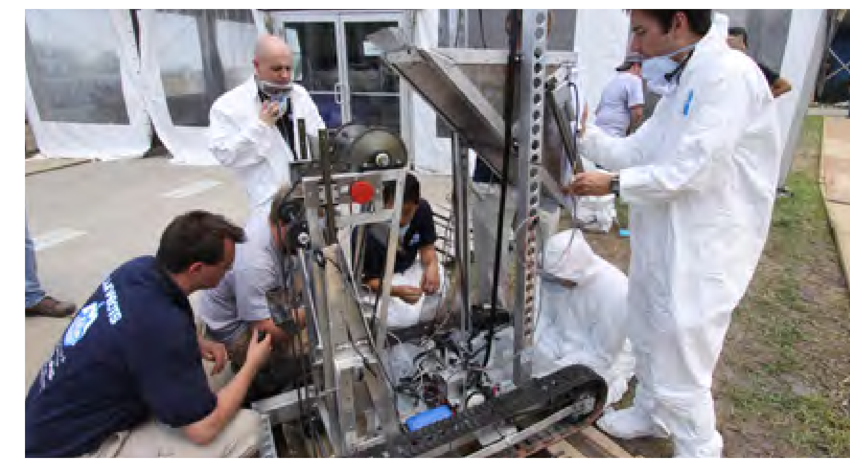
Analog field tests also help inspire and train the next generation of future explorers for space missions. Each of the analog missions provides a host of opportunities to engage with students of all ages and the wider public. These analog missions tie in graduate students conducting research, undergraduate interns competing to develop technologies for use in space, and grade school students learning about the challenges of being an astronaut. Analog teams also reach out to the wider public, and not just through interviews with traditional media outlets. During each mission, analog participants tweet their exploration experiences to thousands of followers on Twitter, answer questions about the day’s exploration activities on Facebook, provide daily blogs by various crew members, and upload hundreds of pictures and videos to Flickr and YouTube. Analog teams are dedicated to inspiring the next generation of scientists and teaching the public about space exploration and the unique possibilities of these missions.

A Decade of Analogs

NASA’s current analog program is guided and funded by the Strategic Analysis Office within the Exploration Systems Mission Directorate’s (ESMD) Directorate Integration Office (DIO). Over the last decade, six analog programs have evolved at remote geographic locations all over the world. Each analog has its own specific mission and focus, and simulates different aspects of space exploration challenges. Two are conducted mostly under water, one each near the North and South pole, two on the sites of dormant volcanic flows, and one on the site of an ancient asteroid crater. Some of these missions have evolved to be an annual mission over nearly a decade, while others have taken place only once or twice. Each mission requires a team of dedicated professionals from a wide range of specialties to conduct the missions, analyze the information gathered, and integrate the efforts into NASA’s larger exploration planning activities. This report profiles six analog missions, with highlights and successes from the last few years, and an overview of the public outreach and education activities by the analog missions.

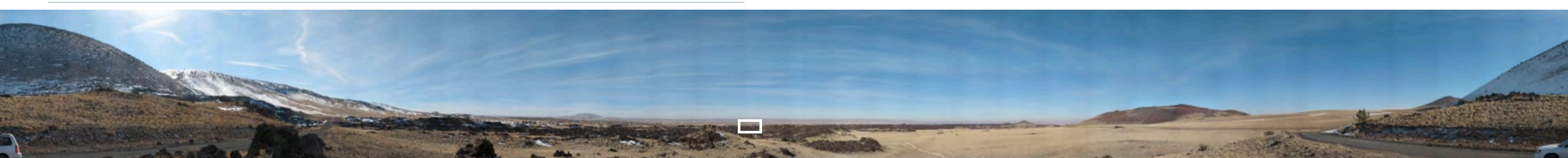
Over the next few years, ESMD has planned activities for five analog missions, to continue answering important questions to make human space exploration safer, more efficient, and less expensive.

Conducting scientific research during analog missions provides NASA with the opportunity to test and improve techniques used for scientific operations in space. Freshwater microbialites are explored at the ***Pavilion Lake Research Project****.*

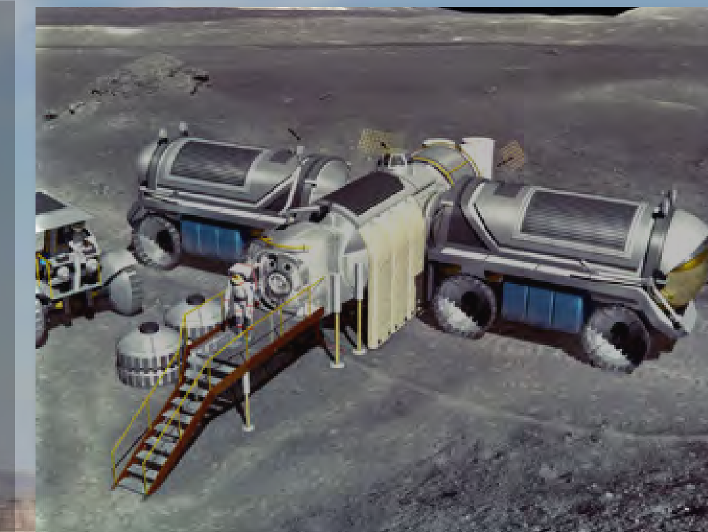


Analog missions provide a unique opportunity to inspire the next generation of space explorers. College student teams work on technologies for the Lunabotics Mining Competition to develop technologies that could one day be used in space.

NASA uses analog missions to reach out to the wider public to encourage participation in current and future exploration activities. An online contest using a GigaPan image invites participants to select where mission teams will explore on their next traverse.



Desert Research and Technology Studies
Desert RATS



Left: Both SEVs docked with the Habitat Demonstration Unit (HDU) at Desert RATS 2010

Right: Artist's conception of two rovers docked to a habitat on the Moon

Desert RATS Fast Facts:

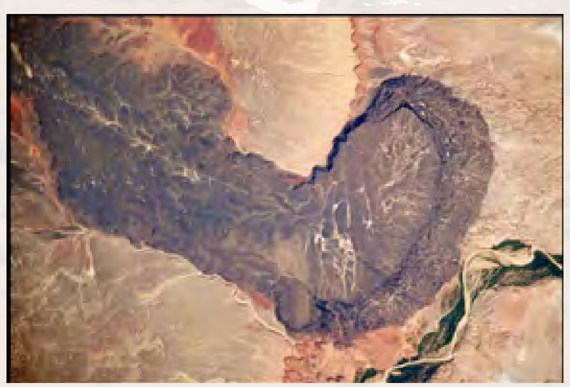
WHAT: Evaluation and testing of EVA and outpost systems and operations.

WHERE: Two-million-year-old lava flow near Flagstaff, Arizona.

WHEN: Annual missions since 1997. The most recent field test was conducted in September 2010.

WHO: Over 200 engineers and scientists, led by Joe Kosmo and Barbara Romig.

WHY: To advance tools, systems, and operations for living on and exploring other planetary surfaces through field testing in a desolate environment with rugged terrain, dust storms, varying soil composition, temperature extremes, meteor craters, steep slopes, rolling plains, and volcanic ash fields.



Black Point Lava Flow, ISS Crew Oberservations August 21, 2009
NASA/JSC Expedition Crew

What are astronauts going to do when they land on Mars? First of all, they are going to walk around—to explore the surface that up until now humans have only seen through telescopes and in images captured by robotic rovers. But going for a walk or a drive on Mars is easier said than done. The human body cannot survive exposure to the harsh environment of Mars or other planetary bodies. To explore the planetary surface, humans must wear, live in, and operate technology that protects them from the extreme environment while allowing them to do the work they were sent to do. The Desert RATS analog study simulates the challenges and operations of planetary exploration, to better understand and improve the technology that astronauts will need to safely explore the surface of a new planet.

The Desert RATS analog study tests roving and extravehicular activity (EVA) operations in an environment that, like the Moon and Mars, features extreme temperatures and difficult terrain. Every year, the Desert RATS program conducts an exploration mission in this setting, which, for the past three years, has been found in Black Point Lava Flow, a complex site and excellent analog for planetary exploration. During each mission, this otherwise uninhabited area is bustling with activity, as experts on scientific exploration, mission operations, astronaut human factors, and advanced exploration technologies come together to help answer some of the biggest questions surrounding planetary surface exploration.

One of the major benefits of the Desert RATS program is its influence on technology development. Because Desert RATS conducts annual missions, it has a "build a little, test a little" approach to technology testing and development. This means that a technology that is tested one year, can be sent back to the drawing board with feedback from the mission, receive the necessary improvements, and return for new testing the following year. These incremental improvements increase the sophistication of the overall exploration system every year. Other benefits of evaluating exploration systems in an analog environment include developing a mature understanding of system requirements that improves the efficiency in schedule and cost during procurement. Analogs also help NASA understand the operational requirements associated with a system or mission as well as evaluate the integration of exploration elements that may not have been co-developed.

Desert RATS studies have enhanced our understanding of how astronauts can live on and explore other destinations, but many questions remain. The Desert RATS study continues to investigate the most effective combination of rovers, habitats and robotic systems; optimum crew size; effects of communication delays; effectiveness of autonomous operations; and how to improve science return. During the 2010 Desert RATS mission, key tests and demonstrations focused on improving productivity on long-duration EVAs, which included pressurized-rover design, operations team make-up and integration, and the impact of infrequent communications.

WHERE

BLACK POINT LAVA FLOW, ARIZONA: 2 MILLION YEARS IN THE MAKING

Black Point Lava Flow near Flagstaff, Arizona is an excellent site for surface system analog field tests, because it shares so many terrain and environmental similarities with the Moon, Mars, and near Earth asteroids (NEAs). Like many planetary bodies, Black Point Lava Flow is a desolate environment with rugged terrain, dust storms, varying soil composition, temperature extremes, deep craters, steep slopes, rolling plains, and volcanic ash fields. Black Point Lava Flow was first considered as a candidate for field testing during the Apollo program, and the site has been used for Desert RATS field tests since 2008.

In addition to its great combination of Moon- and Mars-like features, Black Point Lava Flow is a good analog site because of its large size. The test site is large enough to accommodate multiple extended missions, including day-long scenarios and long-duration (up to two weeks) traverse operations. The area provides enough space to fit the large science and engineering teams of over 100 personnel, who support the tests and demonstrations of Desert RATS every year.

Black Point Lava Flow's Moon- and Mars-like features provide an ideal analog site.

WHEN

D-RATS: EVALUATING EXPLORATION SYSTEMS SINCE 1997

The year 2010 marked the 13th year of annual Desert RATS analog field tests. The first mission was conducted at the Mars Hill area of Death Valley, California, in 1997, and the field test involved a one-week visit of four people to evaluate and assess "what a field geologist does." Since then, Desert RATS has grown. Missions are now approximately one month long, and they have been held at Black Point Lava Flow for the past three years. These missions combine short one- to two-day test missions with one- to two-week traverses. The 2010 Desert RATS mission ran from August 24 to September 16, and the next mission is planned for three weeks in late August and early September 2011.

WHY

EXPLORATION QUESTIONS ANSWERED

The Desert RATS analog focuses on major questions about how to best conduct exploration missions on other planetary surfaces. Over the years, Desert RATS has considered such issues as optimum crew size, habitat solutions, the value of pressurized verses unpressurized rovers, the impact of autonomous verses teleoperated systems, and the best combination of human and robotic systems. Every year, these and other systems and operations concepts are tested and evaluated at Desert RATS, leading to more answers for human exploration and better questions for the following year's mission.

Several Desert RATS missions have pursued the crucial exploration question: what kinds of duties are better performed by robotic assistants and which tasks require human control? After combining different operations concepts and testing different scenarios, the team discovered that robots work best for handling large masses, like deploying communications equipment and charging stations, while humans are better suited for tasks that require more dexterity, like science sample collection and robot control. They also determined that robotic assistance is useful for deploying multimodule systems and for routine inspection and maintenance operations.

Busy Day on a EVA

When astronauts explore the surface of the Moon or Mars, it will be similar to how crewmembers conducted EVAs during their week-long traverses at Desert RATS 2010. This is an example of a typical day on the traverse:

When the rover reaches a designated EVA station, the two crewmembers first record observations of the site from within the rover and document the daily plan for the EVA. Then they perform rover egress operations, which includes getting into spacesuits and performing communications and safety checks with mission control. Once on the ground, each crewmember records his or her planned travel path in relation to the parked rover. During the EVA, crewmembers complete their individual tasks, such as geological observations and sample collection. At the end of the allotted EVA time, crewmembers return to the rover, lay out their samples, and record brief descriptions of each sample. Back inside the rover, the crew records a summary of the day's activities, discussing what was accomplished in comparison to the plan.

Many Desert RATS missions seek to understand how different rover concepts impact EVA operations. The team has evaluated both pressurized and unpressurized rover prototypes under different operational scenarios, and they have discovered that using pressurized rovers significantly extends EVA traverse range and reduces crewmember fatigue. Unlike Apollo, where the crew needed to return to the Lander at the end of each day, researchers were able to use the space exploration vehicle (SEV) as a portable habitat, traveling from one site of geologic interest to another. Exploring in the safety and comfort of a shirt-sleeves environment allows for longer exploration missions, in both time spent and distance covered, while protecting astronaut health and well-being.

In addition to these ongoing demonstrations, the Desert RATS team has specific exploration questions for each mission. The 2010 mission focused on the productivity of the crew and ground support teams with different communication operations under different rover operational concepts, during a 14-day traverse. The team wanted to understand what type of impact a continuous communication approach versus a twice-a-day communications approach would have on the productivity of exploration missions while using rovers in lead-and-trail and divide-and-conquer modes of operation.

To answer this question, the team conducted a long-duration geologic science mission traverse using two SEVs. Each rover was crewed by one astronaut and one field geologist for one-week periods, and these crewmembers were supported by a large science operations team. Both the crew and the team were highly qualified for the mission and trained in the technology and mission operations beforehand. Two communications scenarios—continuous communications and twice-a-day communications—were tested during the traverse mission.

In the continuous communications scenario, the rover teams were in constant contact with the mission and science operations teams. These teams worked with the rover crews in real time, exchanging data and analysis throughout the day and planning daily EVAs together. During EVAs, crewmembers wore a headset to talk

Aerial view of S P Crater and lava flow

Lunar Surface Volcanism

The SEV on a night traverse at Desert RATS and an artist's conception of an SEV on the surface of the Moon

with their partners and the science operations team. This enabled interactive development and testing of hypotheses, complete documentation of observations, and real-time sample cataloguing.

In the twice-a-day communications scenario, communication between the crew and the mission and science operations teams was limited to the beginning and end of each day. Instead of planning EVAs with the science operations team, the rover crews had to follow pre-designed traverse plans or replan the traverses on their own. At the end of each day, the mission and science teams downloaded all of the data that the crew had collected throughout the day. Then the science backroom team was responsible for interpreting all of the EVA data and preparing an assessment for the crew by their next communication window in the morning. These limitations challenged every team member, but because this communication scenario included detailed field procedures, highly trained personnel (both on the field and in the backroom), and the ability to anticipate communication outages, it allowed for a greater science return than a limited communication scenario without these extra features.

Two SEVs on a traverse near Tri-ATHLETE with a habitat mockup

These tests showed that continuous, stable communications, with real-time interactions, between the crew and science support team led to higher quality science samples and data return. The non-field members of the science team understood the geology of the visited sites significantly better during the continuous communications scenario than with the twice-a-day communications scenario. However, in a real exploration mission, continuous communication, though ideal, is both difficult and may not be feasible at some exploration destinations such as NEAs or Mars. This is why the Desert RATS team developed a limited communications scenario that could still achieve substantial science return, and the careful planning and high-quality teams of their twice-a-day communications scenario gave them just that.[3]

LESSONS LEARNED

Planetary Exploration and Science is More than Just Collecting Rocks...

Because rocks and other geological samples offer invaluable information about a planet and its history, the ability to carefully select interesting samples is one of the key reasons to conduct human exploration in space. To test the tools and operations of sample collecting, Desert RATS crewmembers demonstrate sample collection on their EVA missions. In Desert RATS 2010, the crew carried their own suite of tools, which included a rock hammer, tool caddy, tongs, and sample bags. While collecting samples, the crew members found that the tool caddy, which had been designed for accessibility and convenience, was both ungainly and unnecessary. Likewise, crewmembers found that it was easier to pick up a sample with their gloved hands than to use the claw tool. These evaluations allow the Desert RATS team to improve the tool mix in the future and possibly lighten the load by eliminating unnecessary tools.

Astronauts are responsible for collecting more than just rocks on EVAs. They also gather detailed sample and terrain descriptions, using advanced audio and visual equipment, which the astronauts must carry with them somehow. For the 2010 Desert RATS mission, crewmembers were outfitted with a backpack containing advanced electronics, a lower arm-mounted computer, two cameras mounted on the backpacks over the crew's shoulders, and a headset with a microphone for recording field notes. Through analog testing they found that the cameras mounted over the crew's shoulders required crewmembers to lean in awkward positions to get images into view, which was exacerbated by lack of a viewfinder.

They learned that future versions of the technology need a viewfinder in the arm-mounted computer for reviewing images. They also learned that real-time feedback on the audio and visual data will improve data quality and minimize crew workload.

Analyzing and cataloguing all the samples and data collected during an EVA is a big job, and the Desert RATS 2010 team learned that a large science support team can greatly enhance and increase the science return. The analog used two science operations teams: the strategic operations team and tactical operations team. The strategic operations team analyzed the days' events and science return to determine if the planned mission needed changes. They did this for both the continuous and the twice-a-day communications scenarios. The tactical science operations team worked real-time during the day, assessing and evaluating the science and the mission as it happened. In continuous communications mode, this team worked directly with the crew. In delayed communications mode, the tactical team watched and assessed the EVA, but they had to wait until later in the day to communicate their recommendations and findings to the crew.

The EVAs in Desert RATS 2010 produced such a large volume of data and images that the strategic science operations team found it difficult to analyze, integrate, and interpret all the data within the allotted eight hours available at night. The addition of a tactical team to analyze data in real time and support the crew, both with and without communication delays, helped the productivity of mission operations overall. However, future missions will need an improved data system design to facilitate the strategic team's challenging task.

An artist's conception of an astronaut conducting a science EVA on Mars

SUCCESSES

Longer Traverses, More Productivity, Better Science

Working inside the habitat at Desert RATS 2010

Since the inception of Desert RATS, NASA has successfully tested and evaluated equipment, systems, and operations for conducting exploration missions on a planetary surface. Using the build a little, test a little philosophy, the Desert RATS analog continues to build upon its successes and lessons learned from previous field tests.

A significant success story is the constant improvement of EVA traverse distance, particularly the continuing improvement of the pressurized rover mock-up. Human factors evaluations allow for annual improvements to the rovers, and raising the level of astronaut health and comfort in the rovers allows for longer traverses. Over

Astronaut/geologist at Desert RATS

Partnership Success: Green Transmissions

The Challenger Center for Space Education partnered with NASA for the last two Desert RATS analogs, providing live reports and webcasts from the field to students. The webcasts were sent using a solar/wind generator, which provided internet connectivity and served as a cell phone node. The solar/wind generator was donated by Green Trail Energy, Inc.

the past three years, the distance traversed has increased from 140 km in 2008 to 305 km in 2010. In 2010, dual rovers each traversed about 150 km, for a total of 305 km, over 13 nights away from base camp. This is a significant increase over 2008; when although one rover covered 136 km, crewmembers were only able to spend 2-3 nights away from base camp.

The Desert RATS tests also show that by improving the human factors design of the pressurized rover, crewmembers are able to comfortably rest and refresh between EVAs. A significant success of Desert RATS 2010 was that the crews on week-long traverses spent half the usual time on EVA but were 57% more productive. The crewmembers claimed that being able to take breaks between EVAs enabled the increase in productivity. Continued improvements make it possible to plan missions of a month or more, without causing the crew to suffer from exhaustion.

Of course, it takes more than just systems and equipment improvements to impact crew productivity, which is why the Desert RATS team also evaluates different mission operations concepts. In recent years, the analog team evaluated single-person EVAs, nighttime operations, and operations concepts using a combination of pressurized and unpressurized rover prototypes. Desert RATS 2010 successfully evaluated mission operations under varying degrees of communication for two rover exploration operational concepts.

Desert RATS 2010 successfully illustrated that sound crew and science team backgrounds are critical for science operations success. The level of expertise of the science operations team and crewmembers was unprecedented. The science operations team possessed many years of experience as scientists and in conducting field geology tests, while each rover team included an experienced field geologist. Additionally, the operations and rover teams had extensive training with the operations and technology before entering the field. This level of expertise and training resulted in improved science operations over previous analog experiences.

WHAT

ACTIVITIES FROM THE 2010 ANALOG FIELD TEST

The Desert RATS 2010 team demonstrated 10 key hardware elements and 30 technologies for an exploration mission as they conducted operational and communications scenarios. Many systems and technology demonstrations were integrated into the principal mission scenario—a long-duration, coordinated, geologic science mission traverse using two SEVs. The SEVs demonstrated traveling over varied, rough terrain and at varying speeds. The habitat demonstration unit (HDU) in the pressurized excursion module (PEM) configuration was used as a base station and to evaluate the geosciences laboratory, docking procedures, and the suit maintenance area. The 2010 mission evaluated all of these different exploration elements and more, both separately and combined, for productivity, performance, and human factors metrics.

The Desert RATS 2010 team used a number of measures to determine a concept's productivity and effectiveness, including evaluating the daily science return, sites visited, and length of traverse. The HDU-PEM and SEVs were also evaluated for human factors characteristics. The human factors team analyzed over 212 operation elements, including displays and controls, meal preparation, exercise, driving, visibility, and daily habitat operations. They also studied the crewmembers, assessing criteria like workload, fatigue, and comfort during operations. The findings from these investigations allow design teams to continuously improve the SEVs and HDU-PEM, so astronaut teams can be more productive, safe, and comfortable on future exploration missions.

In addition to the SEV and HDU-PEM, many other technologies were evaluated during Desert RATS 2010. The Tri-ATHLETE (All-Terrain Hex-Limbed Extra-Terrestrial Explorer) robotic platform, which would support and carry the HDU-PEM on a planetary surface, was remotely controlled and demonstrated a long-distance traverse with Lunar communication delays. The SEVs demonstrated docking with mobile charging units called portable utility pallets. Crewmembers demonstrated donning shirtsleeve backpacks using suitports connected to the rear of the SEV. While conducting both short- and long-duration EVAs, crewmembers evaluated a suite of geology collection tools and EVA audio visual equipment. Continuing the build a little, test a little legacy, many of these tests will lead to improved technologies and operations for future Desert RATS missions.

WHO

THE TEAM...

Starting with only four personnel in 1997, the Desert RATS field test has expanded to become the largest annual analog mission NASA conducts. The 2010 Desert RATS mission team consisted of over 200 engineers, scientists, and mission planners from 8 NASA centers and universities, with over 100 people in the field during the 14-day mission, including about 40 planetary scientists on the strategic and tactical science teams.

The 2010 mission brought an unprecedented level of expertise to the analog activities. Four teams, each with one astronaut and one accomplished field geologist, crewed the rovers on long-duration EVAs, and a tactical science operations team and strategic science operations team supported each roving team. The science operations teams brought together over 400 years combined experience as scientists and over 35 years experience of conducting geologic field projects. Last but not least, the team was supported by six interns selected to travel to Arizona for the analog. The interns participated in setting up the field test and assisted the teams evaluating teleoperation, communications, and robotics systems.

PARTNERS...

NASA has partnered with international space agencies, industry, and academia on robots and vehicles tested at Desert RATS. Through its Innovative Partnership Program (IPP), NASA has partnered with Caterpillar to develop robotic technologies for moving regolith. General Motors (GM) partnered with NASA to engineer and build Robonaut 2, a humanoid robot, as well as some SEV motor systems. GM's robotic technology used to develop Robonaut 2 has also been infused into other NASA systems, like the Centaur 2 vehicle tested at Desert RATS in 2010. Robonaut 2 is scheduled for field-testing at Desert RATS 2011. The Scarab vehicle was developed through a partnership with Carnegie Mellon University. Mobility testing on Scarab was originally done during the Moses Lake field test in 2008.

Desert RATS 2009 demonstrated robotic sensing equipment developed by MacDonald, Dettwiler and Associates Ltd. (MDA) under funding from the Canadian Space Agency (CSA). The team demonstrated sensing and visualization for obstacle and detection avoidance. This technology, infused into the SEV, uses sensing to look forward and identify obstacles for autonomous driving or to give crewmembers situational awareness.

Lastly, the CSA also participated in Desert RATS 2010, as part of the science operations team.

EVAIS: Good to Have on Hand

The Extravehicular Activity Information Systems (EVAIS) prototype is an electronic system that provides critical information to astronauts conducting EVAs and also provides two ways to record their findings. The EVAIS is contained inside the spacesuit backpack and works with a small flat-panel computer display on the astronaut's wrist, called a cuff display, and a high-definition video camera mounted on the backpack.

The EVAIS provides maps, timelines, and procedures to astronauts while they conduct EVAs. Having this information readily available helps the crew work autonomously, which is necessary when there are communication delays. The EVAIS also lets crewmembers capture audio and video field notes on demand. During testing at Desert RATS 2010, geologists often captured images of their rock samples as they described it for the voice recorder.

...AND YOU!

The Desert RATS team is dedicated to providing students and the public with an interactive and engaging experience. Desert RATS provides hands-on opportunities for students to participate in the analog, including the Lunabotics Mining Competition, in which competing teams of college students build and test lunar excavation robots, and the Moon Work student intern program, which grants a paid internship to the best technology concept proposal by a college student.

Desert RATS offers live interaction with the public on social media sites, including Facebook and Twitter. NASA TV broadcasts and YouTube videos brought the Desert RATS field tests directly to homes and schools. The public was invited to participate directly in the 2010 mission by exploring high-resolution, panoramic GigaPan images of the field site and voting on an area of exploration for the rover teams. This and other participatory exploration activities at Desert RATS are discussed in the chapter Public Engagement and Education, page 52.

Stephanie Wilson and Kelsey Young do an equipment check before an EVA

Moon Work intern Courtney Gras in the rover

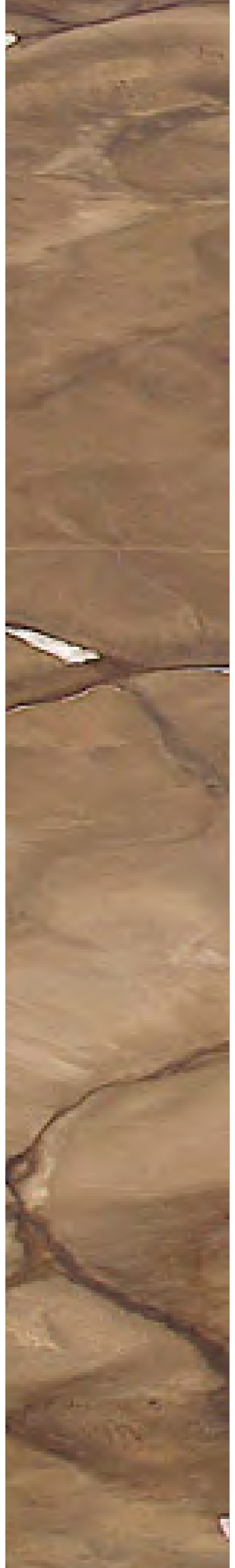
Meet a Team Member: Dr. José Hurtado

Dr. José Hurtado is a geologist and a professor at the University of Texas at El Paso (UTEP). In the first week of Desert RATS 2010, he worked in the science back room, and for the second week, he joined astronaut Mike Gernhardt on a week-long traverse in the SEV.

"[The rover] is an incredible machine for fieldwork. In addition to being able to climb over steep, rough terrain, it also has an array of cameras and a bubble window that allow us to get detailed views of the surroundings," wrote José on the Analogs Blog. José was excited to conduct geology field work in this unique scenario, analyzing the terrain from inside the rover and donning a spacesuit to collect samples. "It has been a productive and fun mission....I'm happy to have the opportunity to help NASA plan for future planetary exploration missions!"

Events and Highlights

- 14-day traverse with full science operations (2010)
- Evaluate pressurized rover with suitports (2009)
- Unpressurized rover demonstrations (2008)
- Lunar outpost assembly demonstrations (2007)
- "Full day in the life" scenario evaluations (2006)
- Two-person simultaneous EVAs (2005)
- Electric Tractor & Chariot assessments (2004)
- Driving tests with rover training vehicle (2003)
- EVA with science trailer & informatics pack (2002)
- 2001
- EVA deployment of surface power (2000)
- First human-robotic testing (1999)
- Suited and unsuited geologic tasks (1998)
- First Desert RATS (1997)



Desert RATS Companion Analog: **Moses Lake**

For two weeks in June 2008, the sand dunes of Moses Lake in Washington State looked like a bustling Moon base, as NASA tested and evaluated several human and robotic systems. NASA chose Moses Lake from over 20 potential field sites for its loose sands, treeless horizons, and soils that resemble the Lunar terrain.

Despite several bouts of inclement weather, the tests at Moses Lake were successful. The analog team, involving members from seven NASA centers, simulated topographic mapping for landing site identification, arrival of a habitat, extravehicular activity (EVA) with spacesuits in an unpressurized vehicle, and habitat docking for outpost buildup.

Testing a Little with a Lot

The Moses Lake field test included some exploration hardware elements that were also tested at Desert RATS, such as the Chariot, ATHLETE vehicles, K-10 rovers, and spacesuits.

The Chariot is a "lunar truck" on six wheel modules that move independently. It can carry cargo, such as small rovers, and up to four suited astronauts standing upright. The independent wheels allow the vehicle to move in any direction and provide a 360-degree field of vision to astronauts. At Moses Lake, the Chariot was tested for remote driving and docking operations, hauling smaller rovers for mapping, and as an unpressurized vehicle for EVA.

The All-Terrain Hex-Limbed Extra-Terrestrial Explorer, or ATHLETE, is a six-legged, robotic, cargo-moving, vehicle. Each wheeled leg has six degrees of motion and can work independently or in concert with the other legs. This level of mobility allows the ATHLETE to tackle many different types of terrain and surface features. Aside from carrying cargo like habitat modules, the ATHLETE's legs can be fitted with tools for digging or drilling. At Moses Lake, ATHLETE was used to move habitats from the simulated landing site to the outpost site, successfully moving and docking two habitat modules, demonstrating NASA's capability to build an outpost.

The K-10 robotic rovers were tested as scout robots at Moses Lake. Scout robots are designed specifically to perform highly repetitive or long-duration tasks, such as the topographical mapping conducted at Moses Lake. The K-10 rovers also tested autonomous operations and long-distance traverses over various types of terrain.

NASA spacesuit engineers also tested hard-bodied and soft-bodied suits during the Moses Lake exercises, wearing them during field tests of the lunar truck and other gear. Testing the new suits in Earth's gravity was grueling work, as some of them weighed about 200 pounds, but engineers learned important lessons. Collecting samples in unpressurized suits (called "Hollywood suits" by the engineers) took 20% longer than the same activity without a spacesuit, while working in pressurized suits took 80% more time.

Where Are They Now?

After the Moses Lake field test ended, many of the demonstrated hardware elements returned to their home Centers with their test results and returned to later missions of Desert RATS with improvements.

Chariot currently supports the space exploration vehicle (SEV), a pressurized cabin prototype that attaches to the Chariot to explore the surface of the Moon, Mars, or near-Earth asteroids (NEAs). Two SEVs were used extensively at Desert RATS 2010.

The second-generation ATHLETE is a coordinated system of two Tri-ATHLETEs, three-limbed versions of the original model. The original ATHLETEs were built at one-quarter of the anticipated final scale, and the new robots are designed at one-half scale. At Desert RATS 2010, the Tri-ATHLETEs carried a mounted, simulated mobile habitat 63 km.

The Moses Lake tests showed that the K-10 rover could operate faster if it could process data on the go, instead of stopping every time it needed to calculate data. The improved K-10 rover tested at Desert RATS 2010 was able to make real-time navigation decisions, moving further and faster than its predecessor.

The ATHLETE tested at Moses Lake in 2008

An artist's conception of two Tri-ATHLETEs on the Lunar surface

NASA Extreme Environment Mission Operations Project

NEEMO

NEEMO Fast Facts:

WHAT: Six aquanauts living and working in a cramped, submerged laboratory to simulate crewed exploration in a hostile environment, with support from surface infrastructure.

WHERE: 3.5 miles off Key Largo, Florida, and 62 feet underwater.

WHEN: Since 2001, NASA has sponsored recurring, multi-week missions, typically in spring and summer. The most recent mission, NEEMO 14, ended on May 24, 2010.

WHO: NEEMO is a multi-organizational analog supported by NASA, NOAA, and the National Undersea Research Center at the University of North Carolina at Wilmington. Through the NEEMO analog, 45 astronauts have become aquanauts.

WHY: To enable training opportunities and assess exploration equipment, procedures, and crew response in an extreme, isolated environment.

Where on Earth can you simulate the challenges of space exploration: where the harsh space environment would quickly kill unprotected explorers, where isolation is the norm, habitats are cramped, and gravity levels are unlike what any human is used to? According to NASA aquanauts the ocean depths provide an analog experience like no other. The NEEMO analog mission uses the world's only operating undersea laboratory, *Aquarius*, to mimic the isolation, constrained habitats, harsh environments, and reduced gravity that challenge space exploration missions.

NASA's recurring NEEMO analog missions provide an opportunity to train crew; conduct behavioral, physiological, and psychological experiments; test hardware configurations; test exploration operations; and perform a host of other exploration-related activities. During a NEEMO mission, NASA aquanauts spend up to three weeks living and working in the watery environment. Just like an interplanetary spaceship or a Martian outpost, the *Aquarius* habitat provides everything the NEEMO crew needs to live, work, and communicate with mission control. Diving suits and oxygen tanks replace spacesuits, and underwater rovers mimic robotic teammates on planetary exploration missions. NEEMO provides an exceptional—albeit very wet—analog to space travel.

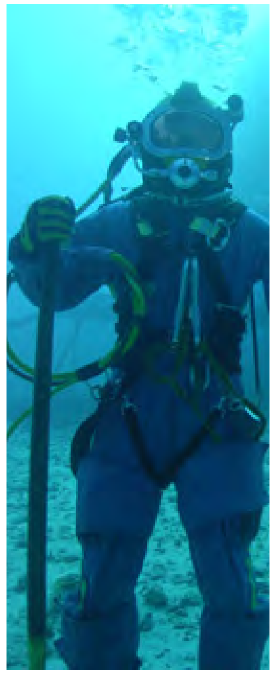
WHERE

AQUARIUS REEF BASE, KEY LARGO, FLORIDA: 62 FEET UNDER THE SEA

The *Aquarius* habitat is a unique underwater laboratory designed to study coral reefs, and it provides a unique analog environment. The *Aquarius* base includes the undersea habitat and laboratory, an ocean-observing platform, and shore-based mission control. *Aquarius* sits about 62 feet underwater—depth varies with the tides—and is 3.5 miles offshore.[1]

The aquanauts spend the majority of the mission in the *Aquarius* laboratory and habitat. The habitat is quite cramped, with only about 400 square feet of living space and 6 bunks—about the same living space as a college dormitory. The cramped quarters resemble tight habitats in current spacecraft, improving the quality of the analog. In addition, *Aquarius* is maintained at ambient pressure. This means that aquanauts can explore the surrounding waters indefinitely, but anyone visiting for more than a few minutes has to spend time decompressing before they

Aquanaut = An explorer who stays underwater for 24 hours or more.



Like spacesuits, diving suits provide protection from an inhospitable environment.

can return to the surface, adding to the sense of isolation common to spaceflight.

Situated on the Conch Reef and surrounded by coral formations, the habitat provides ample sites for marine biology research and analog terrain for simulated extravehicular activities (EVAs). Aquanauts training for exploration missions can traverse a variety of terrain, traveling to depths of 115 feet.[2] Like EVAs on a planetary body, excursions outside the habitat require careful planning. The watery environment constrains mobility and slows activities, while air reserves limit total excursion time. Just like astronauts performing a spacewalk, a team of experts at mission control plans the seawalks.

Characteristic	Space	NEEMO
Harsh exterior environment (no immediate return)	✓	✓
Confined, crowded interior with shirtsleeve environment	✓	✓
Supported by Mission Control Center	✓	✓
Opportunities for EVAs	✓	✓
Supply and consumable management	✓	✓
Research platform	✓	✓
Maintenance and housekeeping	✓	✓

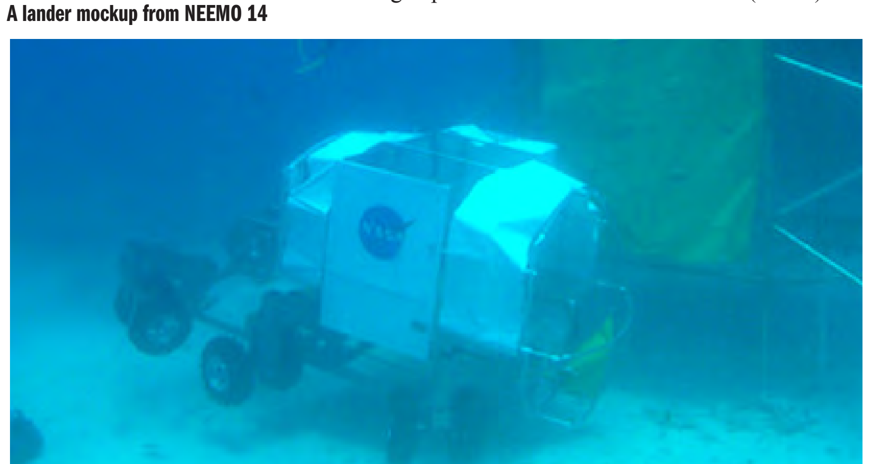
WHEN

NEEMO, THE REOCCURRING EXTREME ENVIRONMENT MISSION

Since 2001, NASA has successfully conducted 14 NEEMO missions in the extreme environment of the *Aquarius* Reef Base. These missions typically occur during the spring and summer, although NEEMOs 1, 4, 7, and 11 were in September and October. Most missions last one to two weeks.

The most recent mission, NEEMO 14, began on May 10, 2010 and ended two weeks later, with splash-up on May 24. The next NEEMO mission, NEEMO 15, is planned for October 2011. NEEMO 15 will include operations simulating exploration of near-Earth asteroids (NEAs).

A lander mockup from NEEMO 14



WHY

EXPLORATION QUESTIONS ANSWERED

Training for Outer Space Underwater

Sometimes seemingly minor questions can identify mission-endangering risks. Issues like the proper load and center of gravity for portable life-support systems or functional angles of ladders in a reduced-gravity environment have to be resolved before developing exploration systems. Just like a stranded turtle on its back, an astronaut with an improperly loaded suit could be immobilized, threatening the mission and risking the crew. NEEMO analog missions answer fundamental questions to ensure safe and successful spaceflight missions.

In a decade of operations, NEEMO missions have answered numerous questions to support future exploration activities. NEEMO's historical objectives include the following areas of current exploration challenges:

- Life sciences
- Engineering hardware development
- Exploration operations, including EVAs, traverse planning, rover operations, construction, and offloading tasks
- Telemedicine and telerobotics investigations
- Sample analysis techniques
- Robotics
- Crew training
- Public engagement, educational outreach, and identifying governmental and academic partnerships and collaborations

NEEMO's crowded habitat, long hours, isolation from home, and harsh environment provide an excellent experimental opportunity for life sciences, specifically studies of the aquanaut crew, including human behavior, physiology, psychology, nutrition, habitation, and medicine techniques. NEEMO missions have similar health challenges to some aspects of spaceflight. For instance, immune responses are suppressed and virus rates are significantly increased for long-duration missions on *Aquarius*, just like shuttle or International Space Station (ISS) missions. As one NASA source notes, "NEEMO is a mission, not a simulation." It provides an opportunity to study these risks in a relevant environment to improve NASA's understanding of how long-duration spaceflight affects the crew's health and performance.

NASA's "build a little, test a little" analog mantra applies to NEEMO as well as other exploration analogs. The NEEMO environment, both inside and outside the habitat, enables testing of exploration equipment designs. Previous mission objectives have sought to test exercise equipment, wireless monitors, and diagnostic systems. The ability to control buoyancy for aquanauts and equipment outside the habitat provides an opportunity for testing equipment designs in their intended gravitational environment.

Buoyancy control provides an unparalleled opportunity for testing exploration operations and simulated hardware. An aquanaut's buoyancy can be adjusted by adding air or weights to the diving gear, simulating different gravitational environments. In the underwater environment, NASA can simulate EVAs, rover interactions, and construction tasks in lunar, Martian, or even NEA gravities. The varied terrain allows NASA mission managers to plan, execute, and evaluate EVA traverses, providing valuable information on the timing of EVAs and how different EVA approaches affect productivity.

Testing communications systems designed to span interplanetary voids is difficult within the limitations of the Earth's atmosphere, much less the 3.5 miles from *Aquarius* to shore; however, NEEMO's communications network allows for artificially induced time delays that simulate the transit time of signals from the Earth to the Moon or Mars. By restricting communications, NASA can evaluate the aquanauts' abilities to adapt and respond to infrequent instructions and varying levels of detail. EVAs with restricted communications provide direct feedback on crew performance and allow NASA to optimize instructions for a variety of communication plans. Previous NEEMO missions have also tested telerobotics and telemedicine procedures with the latency associated with long-distance space travel. Identifying procedures and task orders that work within these communication constraints is vital for maximizing productivity and potentially saving explorer lives.

In addition to these primary activities, NEEMO provides a facility for conducting other exploration-related activities and answering key questions that guide future planning. NEEMO missions have included robotic testing, assessing science sample collection procedures, developing partnerships, and providing an opportunity for public outreach.

LESSONS LEARNED

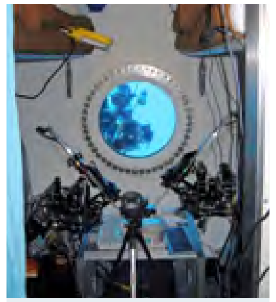
The Underwater Learning Curve

Over the course of 14 NEEMO missions, NASA has worked out many of the kinks in conducting extreme analogs. Lessons learned from these missions feed into future mission planning. Meanwhile, NEEMO remains flexible and relevant to future human exploration, providing an excellent analog for learning new lessons.

From the first NEEMO mission, the analog was designed as an evolutionary exercise. It began as a crew-training mission for the shuttle and ISS, then morphed into an exploration analog. Throughout this process, NASA's

Astronauts rely on analogs like NEEMO to learn how to move in different gravity environments.

An artist's conception of offloading a lunar lander



Telesurgery equipment on NEEMO 12

Telesurgery on NEEMO: Simulating 240,000 Mile Surgical Intervention

On NEEMO 9, NASA, in partnership with SRI International, demonstrated telesurgery with an imposed communications delay of up to three seconds, simulating communication with the Lunar surface. The crew used an M7 surgical robot to perform abdominal surgery on a simulated patient. Subsequent experiments on NEEMO 12 tested advanced surgical techniques with the M7 and Raven robots.

Source: SRI International and NASA

approach to the NEEMO analog has evolved. The first aquanauts relied on traditional scuba gear with limited analog EVA capabilities. The most recent missions, including NEEMO 14, used weighted diving suits to simulate Lunar or Martian gravity. NEEMO 15 will simulate operations around a NEA, including suits with maneuvering thrusters. Throughout this evolutionary process NASA has learned to adapt to new environments and mission constraints.

In addition to general lessons learned, mission managers have picked up a few anecdotal lessons over the course of the NEEMO analog, including lessons about the effects of the high-pressure environment on crew and hardware. For instance, some older hard disk drives are designed to work at standard atmospheric pressure and have a vent hole for equalizing the pressure within the hard drive. At the increased pressure within the *Aquarius* habitat, the spinning disk gets too much lift and can crash, significantly increasing disk failure—up to 50% according to one NEEMO manager. Of course, solid-state drives eliminate this issue, but some of the older NEEMO missions had to adapt and plan for these disk failures.

The increased pressure has caused issues with other equipment. For telerobotic experiments, NASA used sophisticated robotic systems with touchpad interfaces. Because the interfaces are designed to work at one atmosphere, increasing the pressure has the same effect as pushing your hand against all the buttons at once. To fix this issue, NASA's crew used a small hypodermic needle to pierce the touchscreen interface and equalize the pressure. The adaptability and skills necessary to solve these challenges are directly applicable to finding solutions to problems that will be unanticipated in future space exploration missions.

WHAT

ACTIVITIES FROM THE MOST RECENT EXTREME ENVIRONMENT MISSION

On the warm Wednesday morning of May 26, 2010, NASA completed the latest NEEMO mission, NEEMO 14. According to NEEMO project lead, Bill Todd, NEEMO 14 was the most complicated mission yet and covered a range of tasks, including EVAs, equipment tests, crew health, and communications. However, the focus of NEEMO 14 was crew interaction with equipment, tools, and vehicles that NASA may use to explore other planetary surfaces.

One of the primary advantages of NEEMO's aquatic environment is the ability to control buoyancy and simulate different gravity environments, and NEEMO 14 capitalized on this advantage. Of the 22 planned EVAs, 16 excursions focused on evaluating crew interactions with exploration equipment in 3 different simulated gravities and suit configurations. Crewmembers practiced offloading a mockup rover from a lander; tested hatch sizes, ladder angles, and safety systems; tested a lander crane; and simulated loading and unloading payloads. The crew also tested emergency procedures for transferring an incapacitated crewmember from the surface to the lander deck.

NASA also uses this environment to test optimal designs for future spacesuits. Using the Center of Gravity rig, the weight and balance of simulated spacesuits can be adjusted to assess the impact on crew performance. The Center of Gravity rig consists of a reconfigurable backpack with weights that can be added or moved to adjust balance. Aquanauts then perform a variety of tasks in these backpacks, including shoveling, picking up rocks, recovering from falls, and climbing ladders to assess performance. These EVAs help NASA determine the crew's ability to adapt to various gravitational environments when operating exploration equipment. These tests also help NASA engineers design optimal safety mechanisms and crew interfaces. This is especially important when only a few crewmembers are responsible for offloading a vehicle roughly the size of a large SUV from a lander almost as tall as a three-story building!

Aside from EVA activities, NEEMO 14 achieved mission objectives in science, crew health, and communications. NEEMO 14 provided an opportunity to test sample collection tools and processes. Aquanauts conducted traverses accompanied by a remotely operated rover to help identify tasks that benefit from a robotic assistant. Inside the habitat, NEEMO 14 crewmembers participated in behavioral and physiological studies. In one experiment, aquanauts tested ETags, a small wearable sensor that uses radar to passively collect medical data. Unlike other wearable sensors, ETags do not require skin contact or electrodes and provide non-invasive, passive sampling of cardiac performance. NEEMO 14 also tested new communication techniques and protocols, including scheduling tools. The crew performed exploration tasks with a 20-minute-delayed signal to mission control, mimicking a Martian mission.

WHO

THE TEAM . . .

The NEEMO aquanauts are often in the spotlight, however these missions would not be possible without a team of people working toward a successful analog. For every NEEMO mission, NASA aquanauts are accompanied by dive techs from the National Oceanic and Atmospheric Administration (NOAA) Undersea Research Center. The dive techs spend the duration of the mission in the habitat and are responsible for ensuring that *Aquarius* operates properly and the crew remains safe. Topside there is a surface support team consisting of the project and mission leads, the dive medical officer, and support personnel who monitor the team and are responsible for achieving NASA's objectives. In addition, a watch desk team, similar to NASA's mission control, provides 24-hour monitoring of the crew and habitat and are responsible for crew safety and managing emergency situations. Finally, principle investigators oversee the bulk of the science conducted by the aquanauts and periodically interface with the crew for sample collection and analysis.

. . . THE PARTNERS . . .

NEEMO missions require coordination and partnering between numerous government, academic, and commercial organizations. The *Aquarius* habitat is owned by NOAA, and administered by NOAA's National Undersea Research Program. The operations rely on the National Undersea Research Center at the University of North Carolina Wilmington, and the Center works with the Florida Keys National Marine Sanctuary Program.[4] Individual principal investigators (PIs) often lead research tasks from academic and other research organizations. Depending on the mission objectives and PI-led activities, NEEMO personnel often work with non-profit organizations like National Space Biomedical Research Institute and SRI International.[5]

. . . AND YOU!

NEEMO provides a unique opportunity to engage with students and the public across a range of interests. NEEMO personnel provide visual activities for schools or science centers and opportunities to directly interface with NEEMO crew and equipment. For the wider public, the NEEMO analog missions have several venues for public participation and general awareness. The NASA NEEMO Facebook page has information on ongoing and previous missions, links to related pages, and access to pictures and multimedia. Several NEEMO entries can be found on NASA's Analogs Blog (http://blogs.nasa.gov/cm/blog/analogsfieldtesting), and NASAAnalogTV contains video interviews with aquanauts on YouTube. For individuals wanting real-time NEEMO information, NEEMO team members tweet on NASA_NEEMO and *Aquarius* has a general Twitter account at ReefBase.

NEEMO carries with it a primary message for the public: Space exploration and exploration of extreme environments on Earth are incredibly similar. In the paraphrased words of Bill Todd, NEEMO project manager: there is much we can learn from NEEMO, and not just about how NASA can operate in space; but also about how crews and like-minded agencies can work together, operate safely, and achieve a common goal.

Astronaut Eugene Cernan sleeping aboard the Apollo 17 spacecraft

Partnership Success: Even Astronauts Have to Sleep

During the NEEMO 14 analog mission (and a previous Desert RATS mission in 2009), NASA, in partnership with NSBIR, conducted a cognitive performance and stress test. This test was designed to assess the negative impacts of fatigue and identify the best times to perform mission-critical activities. The data from these tests supports normative databases on astronaut performance in analog environments.

Source: NSBIR

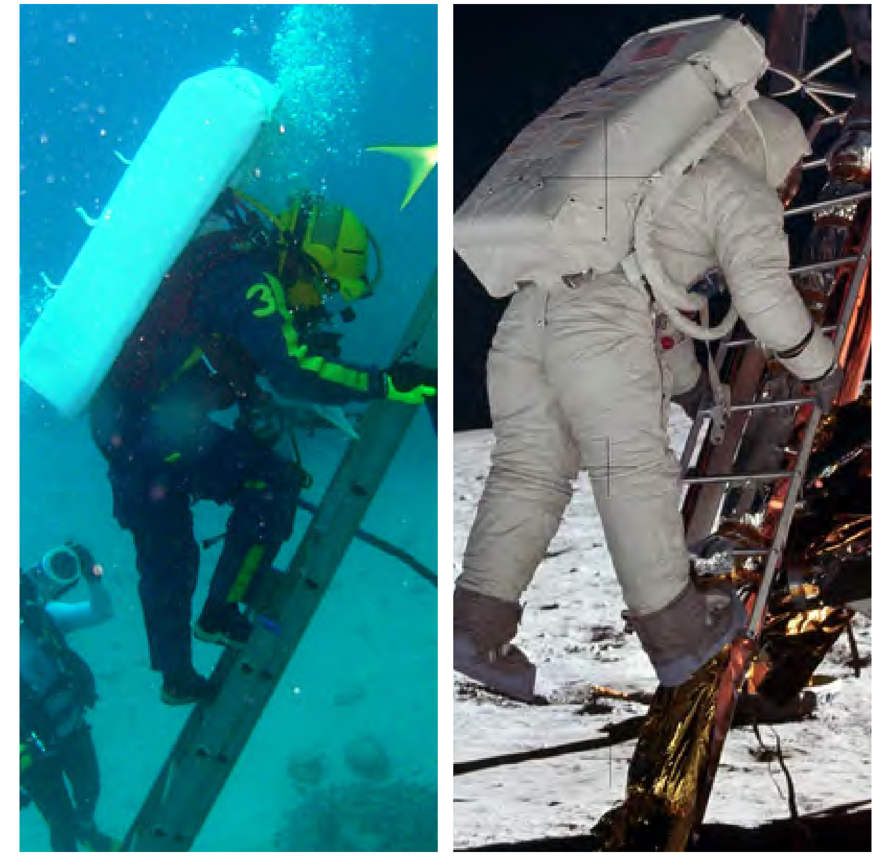
Interview with an Aquanaut: Chris Hadfield

Canadian Space Agency Astronaut Chris Hadfield

On March 25, 2011, Astronaut Chris Hadfield, Commander of NEEMO 14, provided comments on the value of the NEEMO analog. Commander Hadfield is a Canadian Space Agency Astronaut, flew on two shuttle missions, and is scheduled to be the first Canadian Commander on the ISS in March of 2013. NEEMO 14 was Commander Hadfield's first NEEMO mission. Below are some of his remarks on the "most realistic long-duration training environment we have."

Commander Hadfield sees NEEMO, and all other analogs, as a natural extension of NASA's efforts to accurately simulate spaceflight to improve chances for mission success. Many of NASA's simulations reflect the tasks and operations of exploration, but only analogs like NEEMO give NASA an opportunity to simulate the day-to-day psychological environment of spaceflight, thereby providing a vital tool for exploration missions. However, Commander Hadfield provided an important caveat: "One thing you learn, all simulators are wrong." Identifying valuable lessons relevant to the space environment is a key challenge to NEEMO and other analogs. The Commander noted that the only trick to identifying good lessons is operational experience. Thankfully, the "life of an astronaut is decades of simulation."

Commander Hadfield is committed to the value NEEMO provides to space exploration, and he believes NEEMO will continue to be a useful simulation for NASA as the Agency's mission changes. He cites ocean floor EVA opportunities, the ability to simulate various gravity environments, and telemedicine/robotic experiments as evidence that "no matter where we chose as a species to go . . . the things we are doing at NEEMO lay the groundwork."



The underwater environment enables NASA to simulate EVAs, rover interactions, and construction tasks in Lunar, Martian, or even NEA gravities.

Events and Highlights

- 2010
- NEEMO 14: Preparing for Surface Operations
- 2009
- 2008
- NEEMO 13: Autonomous Operations
- 2007
- NEEMO 12: *Aquarius'* 20th Anniversary
- NEEMO 11: Testing Sample Collection
- 2006
- NEEMO 10: Simulating Lunar and Martian Gravity
- NEEMO 9: Long-distance Medicine
- 2005
- NEEMO 8: Remotely Operated Vehicle Teammate
- NEEMO 7: Testing Telerobotic Medicine
- 2004
- NEEMO 6: Supporting NASA's Vision
- 2003
- NEEMO 5: Studying Physiological Effects
- NEEMO 4: Dodging Storms
- 2002
- NEEMO 3: Underwater Construction
- NEEMO 2: Testing Communications
- NEEMO 1: The Mission Begins
- 2001

Haughton Mars Project
HMP

Arctic Analog Mission Fast Facts:

WHAT: Exploration and science research in an international, multidisciplinary field project.

WHERE: Haughton-Mars Project Research Station (HMP RS),
Devon Island, Nunavut, Arctic Canada.

WHEN: 14 missions conducted every summer since 1997.

WHO: : About 100 participants from different institutions and disciplines, led by project lead Dr. Pascal Lee, from NASA Ames Research Center (ARC), Mars Institute, and SETI Institute.

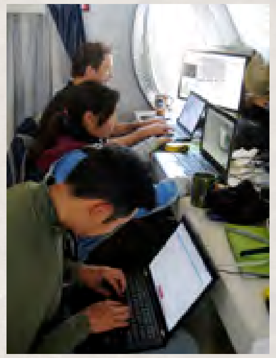
WHY: To advance plans for future exploration of the Moon, Mars, and other planetary bodies, by testing technology and operations in a remote, extreme environment and conducting science research on the Mars-like terrain.

The Haughton Crater resembles the Mars surface in more ways than any other place on Earth. Although other locations, particularly other polar regions, may share Haughton Crater's Mars-like landscape of dry, unvegetated, rocky terrain and extreme environmental conditions, what makes Haughton unique is the crater itself.

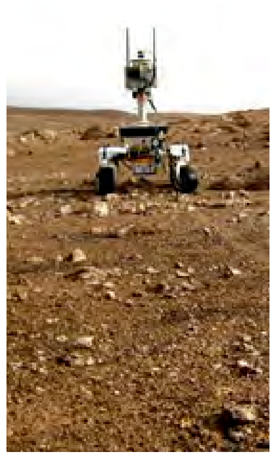
The surface of Mars is covered with craters of all different sizes, so the terrain, like a demolition site, is made up of loose rock. The terrain at Haughton Crater is similarly covered with loose rock, making it a good analog for researching extravehicular activities (EVAs) and mining technologies. Haughton Crater is also a valuable analog for science research, since it contains an uncannily large variety of Mars-like geological features. Also, Haughton Crater resides on an isolated, uninhabited island with no infrastructure, which makes this an ideal analog for planetary exploration research.

The Haughton-Mars Project (HMP) exploration program studies the technologies, strategies, and personnel training that will be used in human exploration missions to the Moon, Mars, and other planetary bodies. HMP researchers test technology prototypes, such as K-10, a robot designed to assist humans before, during, and after human exploration missions. Because the environment is harsh, isolated, and poorly mapped, it provides an analog for testing planetary exploration strategies, such as safety and telemedicine. In addition to its exploration program, the HMP supports a science program, in which the similarities between this crater and the Mars surface offer insight into Mars' geology and climate.

The HMP is an international and multidisciplinary project. Every summer, a group of people from diverse research, education, and cultural backgrounds share the HMP as a home and workplace. HMP accommodates a large variety of research projects and goals, producing many findings and successes, including ways to improve the safety and efficiency of EVA traverses and how to approach planetary protection on Mars. The HMP's science program recently discovered an important finding that may reverse how the science community thinks about the history of Mars' climate. These and other findings support the HMP's ultimate goal: to advance knowledge about other planetary bodies and how to explore them.



Dr. Hans Utz, Susan Lee, and Vinh To of NASA ARC conduct research in cramped quarters.



K-10 on the Mars-like landscape of Haughton Crater.

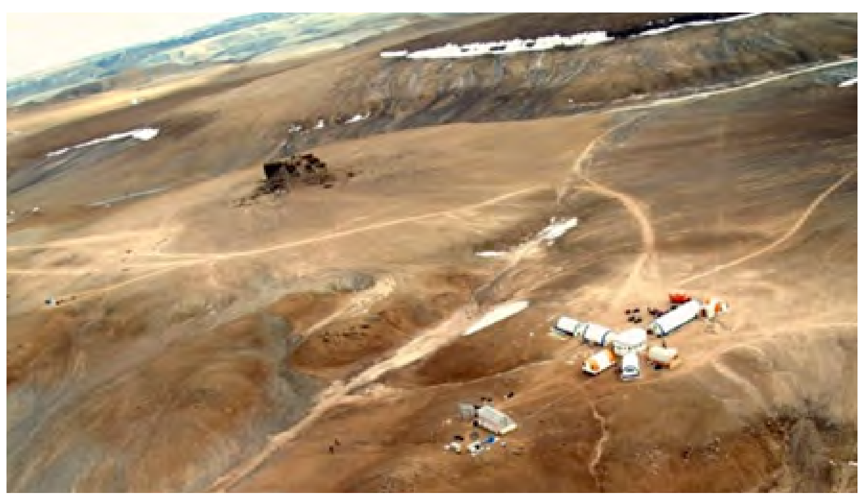
WHERE

HAUGHTON CRATER, DEVON ISLAND: ANCIENT CRATER AS FUTURE DESTINATION

Created 39 million years ago, when an asteroid or comet struck the Earth, the 20-km-wide Haughton Crater is the best preserved complex crater on our planet and the only terrestrial impact crater in a polar desert. The area in and around Haughton Crater offers the greatest combination of Mars-like geological features in one place, including ground ice, rock glaciers, ancient hot springs and lakes, gullies, sapping valleys, valley networks, and canyons. Many of Haughton's features also resemble the Lunar surface, especially Shackleton Crater, a 19-km-wide impact crater at the Moon's South Pole and a potential destination for future exploration.

Fun Fact:
Both the Mars-1 and the Moon-1 Rovers are modified military ambulance Humvees.

Haughton Crater is on Devon Island, the largest uninhabited island on Earth. The largest infrastructure actively used on the vast island is the analog facility Haughton-Mars Project Research Station (HMP RS), located on the rim of Haughton Crater. In addition to supporting about 100 participants every summer, this facility serves as a pilot model for how a future Moon or Mars outpost might be designed and operated.



Aerial photograph of the Haughton Crater and Haughton-Mars Project Research Station (HMP RS)

WHEN

HMP: 15 YEARS OF GROWTH

The HMP became recognized as an analog in 1997, after mission director Dr. Pascal Lee of NASA Ames Research Center (ARC) visited the site to study the crater itself and found that the site held an amazing combination of features supporting Mars analog studies. Since then, annual missions have been conducted at the HMP every summer. The most recent mission was HMP-2010, which ran from July to August 2010. HMP-2011 will be the HMP's fifteenth mission.

WHY

EXPLORATION QUESTIONS ANSWERED

Smart Rovers, Smart Solutions

Like the Moon and Mars, Devon Island presents many challenges for human exploration, including extreme temperatures, remoteness, isolation, and lack of infrastructure or vegetation. HMP researchers use this harsh setting to uncover safer and more efficient ways to explore the extreme environments of the Moon, Mars, and other planetary bodies.

One way to make exploration safer is to have robots do the tasks that do not require human skills or abilities. The HMP has a history of testing robotics, most recently with the K-10 robotic rover. K-10 has been involved in other analog studies, including Desert RATS and Moses Lake, to test its reconnaissance abilities—scouting a site before humans arrive. The HMP team tested a different application for the robot. Instead of using K-10 as a precursor to a human mission, they used the robot to conduct a "follow-up" mission—exploring a site after humans visited and left the site. HMP researchers wanted to know if this activity could lead to more productive and thorough exploration.

The team simulated a follow-up mission with the K-10 at Haughton Crater in 2010. Previously, in the summer of 2009, two geologists unfamiliar with the site traveled in the Mars-1 Humvee Rover, one of the HMP's two simulated pressurized rovers, and conducted short EVAs in concept spacesuits. Then in 2010, the same geologists and science team remotely controlled K-10 from a ground control center at NASA Ames. K-10 used five advanced instruments to collect detailed data about the surface geology and to take high-resolution images.

The team discovered that the difference between robotic reconnaissance and robotic follow-up is that robotic reconnaissance is primarily an initial science approach in which basic knowledge about a site is gained, while robotic follow-up augments and completes human field work. Robotic follow-up is best suited as a more focused science approach, collecting data that the human mission did not have time to gather. In this case, K-10 was particularly useful for geological mapping and for measuring large distributions of subsurface ice. If robotic follow-up is included in exploration missions, this human-robotic partnership could increase the amount and quality of data collection and have a great impact on the value of exploration.

Another way to make exploration easier and safer is to reduce the crew's exposure to contaminants from the space environment as much as possible. To tackle this exploration challenge, Hamilton Sundstrand developed a spacesuit port that allows crew members to move from a pressurized vehicle into a spacesuit safely, easily, and cleanly, preventing dust from the space environment from entering the vehicle.

The HMP tested Hamilton Sundstrand's spacesuit port concept with the Mars-1 Humvee Rover. This port is located on the back of the vehicle, and the spacesuit connects to the port from outside the vehicle. Crew members put on the spacesuit by sliding into it from inside the vehicle. The idea behind the port is that if a crewmember wants to leave the shirt-sleeve environment of the pressurized vehicle and explore outside, she can simply and quickly lower herself into the spacesuit, while sealing the port behind her to protect the inside of the vehicle from dust and other contaminants from the planetary environment. This configuration also allows for extra room inside the vehicle, since the suits are not packed inside, taking up valuable space.

The spacesuit port concept has been under testing at the HMP since 2006, using unpressurized simulated suits weighing 60 lbs, which is how much a future pressurized suit might weigh on Mars. For HMP-2009 and 2010, the Hamilton Sundstrand team expanded the number of participants allowed to test the spacesuit port, so the team could gather lots of feedback about the system. They were never at a loss for willing participants among the team members of HMP, many of whom had waited years for the opportunity to step inside a suit. The HMP-2009 tests proved that a trained participant could operate the spacesuit port with ease and relatively little assistance, but the HMP-2010 tests, using an improved design, revealed that most people, from geologists to the camp chef, could easily enter and exit the suit with only minimal training. The success of the prototype port demonstrates a safer and more efficient way to don and doff a spacesuit and enter and exit a rover.

The Case of the Disappearing Microbes

Since the beginning of the HMP, researchers have pursued one exploration question that concerns the preservation of the unique geological site of Haughton Crater as much as it involves planetary exploration. Because Devon Island is uninhabited, HMP researchers know that they are responsible for introducing human microbes into the environment. This is a shared concern for planetary exploration, an issue called "planetary protection." As they monitored their effect on Devon Island, HMP researchers used the experience as an analog for planetary protection studies.

Project lead Dr. Pascal Lee and the microbiologist Dr. Andy Schuerger together have conducted two studies about human impact on the Arctic. Before the HMP RS

Hamilton Sundstrand's spacesuit port concept with the Mars-1 Humvee Rover.

Planetary Protection

. . . is the term given to the practice of protecting solar system bodies from contamination by Earth life, and protecting Earth from possible life forms that may be returned from other solar system bodies. Planetary protection is essential for several important reasons: to preserve our ability to study other worlds as they exist in their natural states; to avoid contamination that would obscure our ability to find life elsewhere, if it exists; and to ensure that we take prudent precautions to protect Earth's biosphere in case it does.

Fun Fact:
Hamilton Sundstrand developed the suit that Neil Armstrong wore on the Moon.

A canyon on Mars

A sapping valley on Mars

was established, Dr. Schuerger sampled the ground at the site of the future research station. Since then, he has visited the HMP RS three more times to take samples for comparison, and every time, the results are the same: the human microbial impact on the environment appears to be negligible in the surrounding terrain, except at the very site of the research station where it remains minimal. The Arctic is such an extreme environment, especially in the winter, that no detectable amount of human-associated microbes left by one mission is likely to remain until the next mission the following year.

These results are consistent with a similar experiment Dr. Schuerger conducted with Dr. Lee on the Northwest Passage Expedition with the Moon-1 Humvee Rover (a sister vehicle to the Mars-1) in 2009. At each site where the Moon-1 and the expedition team of five spent the night, Dr. Schuerger collected samples of surface snow all around the Humvee, where food had been prepared and consumed just the day before. Later, when Dr. Schuerger analyzed the samples, he found that the presence of human-associated microbes was barely detectable if at all. HMP researchers reason that since the Mars environment is more hostile to human life than the Arctic, and since humans will be contained within spacesuits, it is likely that humans will have at most an extremely limited environmental impact on the Martian surface. More data over time and analysis at other sites and during more expeditions are necessary, but so far, these baseline studies provide some good news for planetary protection concerns for Mars.

Dr. Pascal Lee and his trusty sidekick, Ping Pong.

LESSONS LEARNED

Toward Safe and Efficient Exploration

Some of the most important lessons learned from the HMP were developed over years of experience conducting mock EVAs on Devon Island with simulated rovers. The HMP has used ATVs (all-terrain vehicles) as individual personal transportation vehicles in the field since 1997, and in 2003, the HMP welcomed the arrival of the Mars-1 Humvee Rover, a simulated pressurized exploration vehicle. After years of driving the Mars Humvee on mock EVAs and with the addition of the Moon Humvee in 2009, HMP researchers have discovered the importance of having multiple vehicles on a long-duration roving mission.

Sometimes even the most advanced technology meets an obstacle it cannot overcome, and on Devon Island, HMP researchers experienced cases where the Mars-1 Humvee became stuck on rough terrain or on terrain that was too soft. This led to two important lessons learned:

- As Dr. Lee puts it, "Sand on Mars will be the killer." Both Mars exploration rovers, Spirit and Opportunity, have experienced issues with getting stuck in sand, and as the HMP experiments show, humans on Mars, and even on the Moon, will need to be prepared for similar issues affecting a larger vehicle on Mars.
- Some sort of vehicle back-up, either unpressurized rovers or a second pressurized rover, is necessary on any long-range or long-duration crewed traverse. HMP researchers always have two or three ATVs accompany the Humvees on traverses, so that if the Humvee experiences a problem, one or all ATVs can return to the camp site for help or transport the crew.

Dr. Lee and the rest of his crew experienced the impact of this lesson learned when the Moon-1 Humvee Rover encountered four major mechanical breaks during its perilous voyage on sea-ice along the Northwest Passage to Devon Island in May 2010. At one point, the Moon-1 was stranded on sea-ice and could only be fixed by borrowing a part from the Mars-1 on Devon Island, so two snowmobiles were sent ahead to the HMP RS to retrieve the needed part. When the crewmembers on snowmobiles returned with the spare part, the crew was able to repair the Moon-1 and get it onshore Devon Island safely. The team's preparation helped avoid a catastrophic loss, and the knowledge gained from the experience will inform and improve the safety of future planetary exploration missions.

The HMP will test a new technology approach in 2011, as a result of a lesson learned at a different analog site. In 2008, Dr. Lee participated as a rover crewmember in a Desert RATS analog mission at Black Point Lava Flow, Arizona. During the mission, Dr. Lee participated in several traverses to examine rocks and collect samples. On one of these traverses, Dr. Lee noticed that crewmembers had to go on a spacewalk to collect rock samples, physically chipping at rocky outcrops with a hammer. Meanwhile, Dr. Lee recalled that in the Apollo missions, astronauts picked 95% of their rock samples right off the ground with a scoop, because so much of the Lunar surface is covered with loose rock, or "float," and not rocky outcrops. Dr. Lee considered that sampling can be made easier, faster, and safer if loose rocks are collected with a robotic arm attached to a pressurized rover. The Desert RATS analog site Black Point Lava Flow does not have much float, but because Haughton Crater is an impact site (like most of the Lunar surface), it has a lot of float. 80% of the rocks collected at the HMP are found as loose rubble, which makes it a good site to test the robotic arm concept.

Dr. Lee estimates that collecting rock samples with a robotic arm can reduce EVA time by about 50-80%. This concept reduces the number of necessary spacewalks, which saves time from donning and doffing spacesuits, walking on the surface, and chipping at rock. More importantly, the robotic arm concept increases safety, because staying inside the shirt-sleeve environment of a pressurized rover is safer and easier for crewmembers. This idea will be tested during the upcoming HMP-2011 mission, with a new robotic arm attachment on the Mars-1 rover.

In addition to inspiring an operations and technology change, this experience also taught an important lesson about conducting analog studies. Because Dr. Lee knew the Haughton Crater terrain so well, he was able to compare the benefits and challenges of the Desert RATS and HMP sites. The benefit of having analog scientists participate in different analog studies is an important lesson learned for all of these missions.

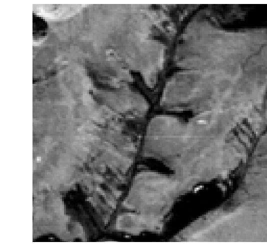
SUCCESSES

In Technology, Operations, and Science

Some of the HMP's accomplishments are from successful technology demonstrations, like the ongoing automated drill project. Since 2004, Dr. Brian Glass of NASA ARC has led the Drilling Automation for Mars Exploration (DAME) project at the HMP. The DAME project has led to the advanced Construction and Resource Utilization Explorer (CRUX) Drill, which experienced some significant successes in 2010. The CRUX Drill team successfully tested the rotary-percussive drill's ability to detect potential failures and perform recovery actions to correct itself. This means that the drill can operate on its own, without any physical human assistance—an important step for planetary exploration, since autonomous drilling can help prepare a site for human arrival, by mining necessary resources or beginning outpost construction. The CRUX Drill team also developed a unique downhole imager—a compact and durable camera nestled inside a wired drill bit—which successfully returned images from deep below the surface.

In addition to technology tests, the HMP has conducted successful exploration operations studies as well, like the telemedicine project conducted in 2009. For this project, nine scenarios were simulated in which both doctors and participants with little medical knowledge were instructed remotely (by another doctor via webcam) on how to perform necessary life-saving procedures. Participants with no medical background were able to successfully conduct such extreme procedures as mending an amputated leg on a simulated robotic patient.

On the science front, one success for the HMP was a discovery that could change the way scientists think about the history of Mars' climate. Images of valleys and canyons on Mars show signs of erosion that many scientists believe is caused by the flow of water in open air. Mars is too cold to have water flowing in open air without freezing, which leads many to believe that Mars was once



A canyon on Devon Island, Earth

A sapping valley on Devon Island, Earth

The advanced Construction and Resource Utilization Explorer (CRUX) Drill.

Setting Records

The start of the HMP-2009 and -2010 missions embraced a new challenge: driving the Moon-1 Humvee Rover across the Northwest Passage, a 500-km trek on sea-ice. The 2009 mission traveled in unfriendly arctic conditions for eight days before reaching the expedition's first goal. The 2010 mission successfully completed the expedition after 13 days of traversing treacherous stretches of snow-covered island and rough sea-ice. This expedition holds the world record for longest distance traveled on sea-ice in a road vehicle.

warmer, wetter, and had a thicker atmosphere. There are issues with this hypothesis, including the Faint Early Sun Paradox: how could Mars have been warmer back when the Sun was dimmer and have become cold while the Sun became brighter? Because Devon Island shares so many geological similarities with the Mars surface and climate—both are cold and dry and contain valleys and canyons—HMP researchers were able to draw a new conclusion about the formation of Mars' geology and the history of its climate. They know that the climate at Haughton Crater has always been cold and dry, and they discovered that its valleys were formed by melting ground ice, and its valley networks and canyons were formed by the movements of glaciers. It is possible that similar processes occurred on Mars, meaning that Mars may have been always as cold it is now, if not colder. Not only is this a success for the Haughton Crater analog, but finding a way to resolve a troubling paradox is also a success for the entire science community.

WHAT

EXPLORATION ACTIVITIES IN THE ARCTIC

The typical HMP mission begins with field deployment and camp preparation in late June or early July. Participants fly out of the nearest town, Resolute Bay, on a one-hour flight to Devon Island aboard a Twin Otter plane. Upon arriving at camp, all participants undergo field safety and survival training. Field research runs daily in July and August.

Visitors to Haughton Crater sleep in a personal tent during their stay, but all work and recreation is conducted in the more comfortable common-use tents of the HMP RS outpost or out in the field. The station is made of several modules, including a command module, two lab modules, a systems module, a medical operations module, a garage and workshop module, and a living "mess" module, all of which surround an octagonal central hub called the Core. When weather conditions prevent field work, everyone is confined to the outpost, increasing the similarities to a planetary outpost.

Some mission activities, such as telemedicine research, is conducted at the outpost, but most of the research experiments at the HMP are conducted in the field. Any research requiring traverses, such as testing the simulated exploration rover, the K-10 robot, simulated spacesuits, exploration information systems, and EVA tools, is performed at a distance from the outpost. Some technology experiments, such as the CRUX Drill, require testing in an area with impact rubble and ground-ice. Of course, any research into the history of the crater itself or nearby canyons and valleys also involves time spent outdoors.

Different projects run simultaneously during an HMP mission. Some experiments are tested at the analog once, and others go home for improvements and then return for more testing in a future mission. A list of a few projects conducted at the HMP over the years can be found in the timeline at the end of this chapter.

WHO

THE TEAM...

The HMP participants come from diverse backgrounds in terms of scientific discipline, research experience, education, organization affiliation, age, gender, and ethnicity. One unifying element among these different people is their passion for exploration. Plus, they all possess the courage to withstand the arctic climate.

For each mission, up to 30 people reside and work at the field site at any given time, with about 10 people spending the entire length of the mission on Devon Island, while other co-investigators and visitors rotate in and out. One of the permanent summer residents is project lead Dr. Lee, along with his dog, Ping Pong, who also spends her whole summer at the field site.

In an average mission, the HMP is supported by multiple scientific teams conducting research, which often includes several graduate students; geologists and microbiologists; two spacesuit engineers from Hamilton Sundstrand; a base camp manager; a safety officer (often a medical doctor); field technicians and guides; an education and outreach coordinator; and a camp cook. Other visitors include writers, artists, news reporters, and film crews. Additional support is provided by a ground control center at NASA ARC or NASA Johnson Space Center. Ground control is particularly involved in the projects requiring remote operations, such as telemedicine experiments, working with autonomous robots, or interfacing with crews conducting a traverse or EVAs.

PARTNERS...

The HMP is a large, international, and multidisciplinary venture, involving several major entities working with NASA, including:

- Mars Institute
- SETI Institute
- Canadian Space Agency (CSA)
- Polar Continental Shelf Project
- National Space Biomedical Research Institute
- Hamilton Sundstrand
- Honeybee Robotics
- MDA-USA
- SpaceRef Interactive
- AM General LLC
- Kawasaki Motors USA
- Many different universities every year
- Nearby Arctic communities of Grise Fiord and Resolute Bay

These and other organizations provide combined support to the HMP, develop the research projects for testing in one or multiple missions, and provide the personnel to conduct mission studies and operate the outpost. For example, in 2002 SpaceRef Interactive donated an autonomous greenhouse, called the Arthur Clarke Mars Greenhouse, to the HMP RS. Since then, the CSA, the University of Guelph, Simon Fraser University, and the University of Florida have operated the greenhouse remotely throughout the year and on site for one month a year. This collaboration has led to new successes for the greenhouse every year and new hope for eventually growing fresh food on another planet.

Meta a Team Member: Kelsey Young

Kelsey is a Ph.D. candidate in the School of Earth and Space Exploration at Arizona State University. While earning her undergraduate degree at Notre Dame, Kelsey became interested in how analogs can be used to answer questions about human space exploration.

"As we move toward the next generation of planetary surface exploration, we must develop the necessary technologies and mission planning protocols needed to explore beyond Earth," says Kelsey, "Terrestrial analog projects are a crucial part of this goal in that they help to both develop necessary exploration technologies as well as explore scientific problems on other planets by looking closer to home. Haughton Crater is a perfect place to investigate these issues in that we can examine impact cratering processes as well as field test the logistics of exploration." Kelsey was involved in both of these activities at HMP-2010.

Kelsey traveled to Devon Island in 2010 to support both the exploration and science research at the HMP. She was one of the on-site team members planning traverses for the K-10 rover, helping K-10 react to real-time decision making problems. Kelsey also studied Haughton Crater itself, collecting impact breccia samples to more accurately date the crater.

A truly dedicated analog researcher, Kelsey headed to the Desert RATS 2010 analog field test immediately after returning from the HMP mission, to participate as a rover crew member. "It gave me a different perspective," said Kelsey in an interview, "Being involved in both analogs was a great opportunity."

...AND YOU!

The HMP engages with the public through many different forms of media. The HMP team updates their mission status daily on the analog's website, http://www.marsonearth.org/, as well as on Twitter and Facebook. Not only does the team provide detailed reports about the many different activities performed throughout the day, but it also shows these events as they happen, in hundreds of photos available on Flickr and in videos on YouTube. In HMP-2010, 14 videos of interviews with different researchers and team members provided a behind-the-scenes look into the many different projects, technology tests, and camp operations of the HMP mission. Other media productions include the more than 13 international documentaries filmed at the HMP within the last 15 years. Finally, HMP researchers have published their findings and activities in over 75 peer-reviewed publications and NASA technical reports.

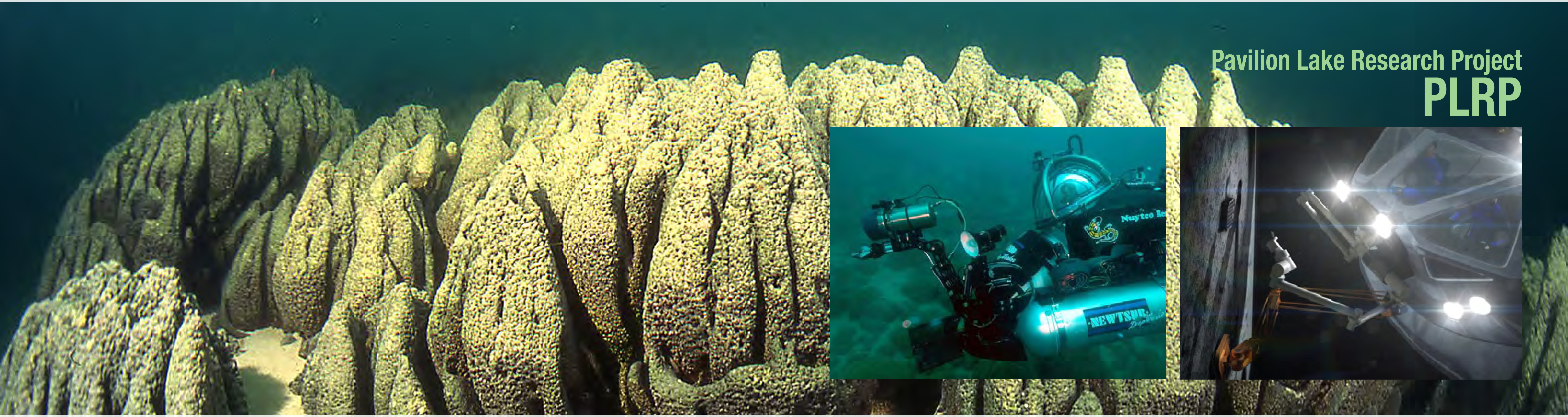
Partnership Success: Special Delivery!

Science and technology institutions are not the only organizations supporting the HMP. Since 1999, U.S. Marine Corps and Air National Guard C-130 crews have provided substantial logistical support to the project, including transportation of tens of tons of mission critical cargo, such as exploration vehicles, expeditionary gear, research equipment, and field supplies.

This cargo is sometimes "paradroppped"—delivered airborne on parachute-equipped cargo pallets. The Marine Corps and Air National Guard consider the HMP a valuable training opportunity, since it offers the challenge of some of the highest latitude operations possible, often combined with extreme logistics and weather conditions.

Events and Highlights

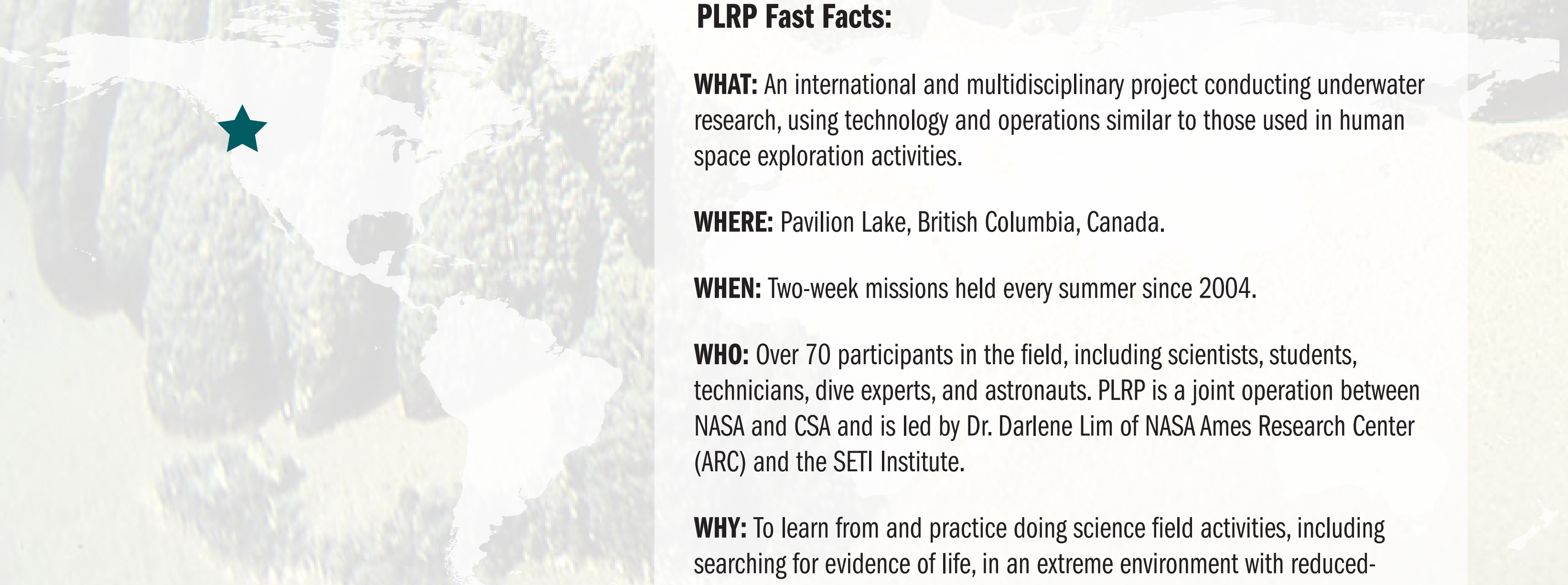
- 2010 — Medical immunology research
- 2009 — Enhanced communication infrastructure
- 2008 — Traverse Planning Software
- 2007 — Robotic survey with K-10 Red and K-10 Black
- 2006 — Simulated medical rescue EVA
- 2005 — MIT Space Logistics Project
- 2004 — First DAME test
- 2003 — BEES for Mars flights
- 2002 — Arthur Clarke Mars Greenhouse installed
- 2001 — Hyperion sun-synchronous rover tested
- 2000 — Advanced planetary exploration spacesuit
- 1999 — HMP formally established
- 1998 — Science and exploration research begins
- 1997 — Haughton recognized as analog site



Pavilion Lake Research Project
PLRP

Left: Exploring underwater in a submersible

Right: Artist's conception of a Space Exploration Vehicle (SEV) exploring a near-Earth asteroid (NEA)



PLRP Fast Facts:

WHAT: An international and multidisciplinary project conducting underwater research, using technology and operations similar to those used in human space exploration activities.

WHERE: Pavilion Lake, British Columbia, Canada.

WHEN: Two-week missions held every summer since 2004.

WHO: Over 70 participants in the field, including scientists, students, technicians, dive experts, and astronauts. PLRP is a joint operation between NASA and CSA and is led by Dr. Darlene Lim of NASA Ames Research Center (ARC) and the SETI Institute.

WHY: To learn from and practice doing science field activities, including searching for evidence of life, in an extreme environment with reduced-gravity conditions.

On the surface, Pavilion Lake is a serene recreational lake, but below the surface is a whole other world. The walls and floor of Pavilion Lake are covered with microbialites—carbonate structures that form underwater into a variety of unusual shapes, often with the help of microorganisms. These strange, rare structures are similar to ancient fossilized stromatolites, some of the earliest remnants of life on Earth. Studying these microbialites might reveal information about early life on Earth, and this activity may influence how space explorers search for evidence of ancient life on other planets.

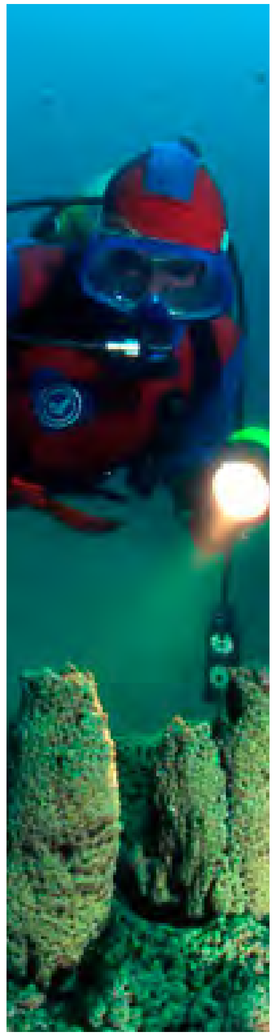
The Pavilion Lake Research Project (PLRP) attracts scientists from multiple disciplines, working together to characterize the microbialites of Pavilion Lake while testing strategies for space exploration. Underwater exploration shares similar challenges and approaches to space exploration. For example, humans cannot breathe underwater or in space, so exploration in either environment requires remote operation of sophisticated robotic systems or a human in a pressurized vehicle. Both scenarios also require that data be sent to a command center, where it can be sorted and analyzed by scientists. These and other similarities make the PLRP a good analog for researching science and exploration operations for missions to the Moon, Mars, near-Earth asteroids (NEAs), and other destinations.

While advancing science and science operations, the PLRP also provides a "mission of opportunity" for astronaut training designed around real field research activities. As they operate submersibles to study microbialites, astronauts gain hands-on experience observing and recording scientific data in an extreme environment. Astronaut and scientist feedback provides valuable input on fatigue, workload, data quality, and the scientific merit of observations.

WHERE

UNDERWATER IN BRITISH COLUMBIA

Pavilion Lake is located in British Columbia, Canada, northeast of Vancouver. The lake itself is 3.7 miles (6 km) long, 0.6 mile (1 km) wide, and 213 feet (65 m) deep. Scuba divers can swim only to the shallow depths and cover a limited distance, so the breadth of the large lake must be explored with either autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), or pressurized single-person vehicles called



Examining microbialites

DeepWorker submersibles. Even in the summer, the deeper portion of the lake does not get warmer than 40° F (4° C), so, like spacesuits and exploration vehicles, all diving suits and crewed equipment have to be insulated against the low temperature.

The lake contains some of the largest and most diverse freshwater microbialites known today, with a wide range of size, shape, and depth. The microbialites are rare and delicate, so divers have to be careful operating heavy equipment around the structures, just as a crewed exploration will have to protect the environment of another planet.

WHEN

SEVEN SUMMERS AND COUNTING

The project's principal investigator, Dr. Darlene Lim, established the PLRP after her first field season at Pavilion Lake in 2004. Since then, PLRP field activities have run for about two weeks every summer, though the mission officially begins with months of planning beforehand. The 2010 mission planning began in the Fall of 2009, and field operations were conducted over a two-week period beginning June 26. The schedule for 2011 begins with the Draft Protocol Meeting on May 27, with the field season planned for ten days beginning on July 16.

WHY

EXPLORATION QUESTIONS ANSWERED

Itinerary vs. Opportunity

Balancing scheduled operations with discovery opportunities is critical to a productive exploration mission. When exploring in space, the crew must adhere to a planned sequence for some tasks and safety measures, but there are occasions where the crew will have to decide whether they can interrupt the mission plan to take advantage of an important science opportunity. As Dr. Lim told an online publication, "It would be a real shame to send somebody all the way to Mars and have them miss the alien, right?"[1] The PLRP simulates space exploration science operations to learn how crew members can make these crucial decisions and have a productive mission.

Research at the PLRP has demonstrated that the best way to prepare for a productive science mission is to gain experience in making these kinds of decisions. Several astronauts have participated in the PLRP as DeepWorker pilots, immersing themselves in a science mission that resembles the environmental challenges and stress factors of space exploration. While piloting the DeepWorker submersibles, these astronauts and other researchers must maximize the limited amount of time they have to conduct each flight, while collecting useful scientific information. This involves constantly monitoring their air supply and the craft's battery power, steering the sub around the microbialite formations at very close range, operating the camera to ensure good footage, and recording verbal scientific observations. The PLRP found that as the astronauts gained more experience in this challenging situation, they improved their ability to decide when to pursue a science opportunity or follow the strict schedule. The researchers at PLRP believe that participating in different kinds of analogous field activities will be a great way for astronauts to prepare for space exploration activities.[2]

LESSONS LEARNED

In Cooperation and Communication

In 2010, the PLRP team tested two different ways to coordinate robotic science missions, comparing joint objectives against joint missions. To evaluate missions with joint objectives, the team sent out an AUV and a DeepWorker at different times but on the same flight path. The researchers found that to compare the collected data they had to use high-precision georeferencing tools and that the time-stamping of the two missions had to be perfectly aligned. To evaluate joint missions, an AUV and DeepWorker explored an area together. From this experiment, the researchers learned that the greatest difficulty in coordinating the robotic mission was determining a safe distance between the two vehicles. They found that the AUVs could safely explore within 23 ft. (7 m) of the DeepWorkers.

The 2010 PLRP field activities also learned lessons in communication operations. This was the first mission where the team was able to stream audio from the DeepWorker pilots (who speak notes out loud while making science observations) to researchers on the surface, rather than analyzing the voice recordings after the field activities ended. The team learned that being able to hear the pilots' notes as they explored underwater allowed the team to plan better flights for later in the mission, sometimes modifying flights within the same day. For the 2011 mission, the PLRP team wants to incorporate two-way communication with video as well as audio, to see if science missions will be more productive when the pilots receive input from a science back room.

SUCCESSES

Better Mapping, More Productivity, New Opportunities

An ongoing success at the PLRP is the continued improvements to mapping the lakebed. This success is largely due to the technology advancements happening with the project every year. The DeepWorker submersibles were one of the first great steps toward improving mapping methods. Before the DeepWorkers were included in the project, most of the mapping of the lakebed was performed by SCUBA divers, and areas too deep for divers were covered by programmed AUVs or remotely controlled ROVs. The introduction of DeepWorker submersibles in 2008 made it easier for researchers to survey larger areas, enabled longer dive times, and provided the ability explore new depths in person.

In 2009, the PLRP took the research a step further with in-field data synthesis and analysis. Previously, the massive amounts of data collected during DeepWorker flights (about 25 gigabytes of video per flight) could not be analyzed until after the field activities ended for the season. For the 2009 mission, however, the PLRP team set up chase boats equipped with navigation computers to track the DeepWorkers' positions every five seconds and build a real-time map of the flight path. Meanwhile, a stenographer aboard the boat listened to the pilots' observations on the voice loop to transcribe important notes and link them to the submersible's location on the map. Significant events on the video feed were also linked to their corresponding locations on the map shortly after the flight was completed. Consequently, rather than waiting a year to revisit areas of interest, the PLRP team was able to modify or create flight plans before the end of the field season. This process streamlined science operations significantly, allowing for greater science return and a more productive field season overall.

Another PLRP success opened new opportunities for one of Pavilion Lake's close neighbors: Kelly Lake, a smaller lake that also contains microbialites. In July 2010, PLRP researchers conducted AUV and ROV missions at Kelly Lake for three busy days. They collected large amounts of useful data, including side-scan sonar, color video, water quality measurements, and 50 km of geoacoustic mapping.[3] Because of the group's thorough data collection and quick data processing, the PLRP team was able to plan an exploration mission for Kelly Lake in 2011. The MARSLIFE project, which explored microbial biomarkers in Pavilion Lake in 2010, will extend to Kelly Lake in 2011. Involving Kelly Lake in submersible operations also creates new opportunities for testing long-range and time-delayed communication exploration scenarios at the PLRP.

WHAT

ACTIVITIES IN EXPLORATION AND SCIENCE RESEARCH

The exploration activities at Pavilion Lake center on real science missions. The PLRP team uses DeepWorker submersibles, AUVs, ROVS, and SCUBA divers to make science observations and collect data (primarily through high-resolution images) about the vast microbialite community covering the walls and floor of the lake. This part of the PLRP analog is most likely to inform astronaut training techniques; how to conduct efficient extravehicular activities (EVAs); how to manage time on science operations; and how to determine the right balance in the use of autonomous robots, remotely controlled robots, and crewed rovers in future space exploration missions.

The underwater exploration activities at the PLRP yield massive amounts of data, and a huge bulk of the science operations, both during and after the field season, is devoted to sorting and analyzing that data. To understand how microbialites form, the PLRP scientists spend countless hours studying thousands of microbialite images, sorting them by a classification system designed

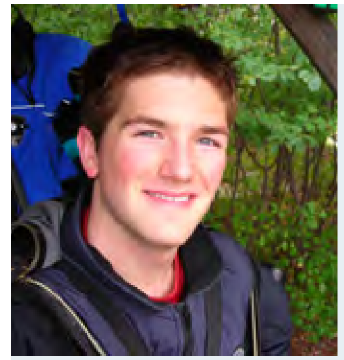
What is a DeepWorker?

The DeepWorkers are single-seat submersibles developed by Nuytco Research. A DeepWorker is just big enough to hold a single pilot, a few electronic systems, and some life support and survival gear. The vehicles also have a small hydraulic manipulator similar to the robotic arms used on the Space Shuttle and Space Station.

DeepWorker excursions, called flights, usually average about two hours. In 2010, the DeepWorker schedule included some longer flights lasting nearly five hours, as well as two night flights. The team of 6 scientist pilots, which included 2 astronauts, performed 34 DeepWorker missions in 10 days.

by the researchers. Beginning in 2010, some of the PLRP scientists were also involved in real-time analysis of exploration data, which involved creating detailed maps of the lake and designing flight plans. Finally, the team also analyzes data to evaluate missions operations and find ways to improve exploration missions. This analysis is usually performed months after the field activities have ended, but in 2010 some of the real-time data processing allowed for quicker analysis and assessments.

In addition to studying microbialites and exploration operations, another ongoing project at the PLRP is developing performance metrics to measure the quality and efficiency of scientific exploration. Every year, the PLRP team studies different factors of science operations, including science merit, fatigue, workload, observational quality, and data quality. During the 2010 field activities, the PLRP recorded specific metrics before, during, and after DeepWorker flights. The team measured scientific merit by comparing what they planned to achieve from a flight against what they did achieve by the end of the flight. As these performance metrics become more defined and useful, members of the PLRP team visit other analog sites, including the Mauna Kea ISRU and Desert RATS analogs, both to gain new information and to share what they have learned.



Meet a Team Member:
Tyler Mackey

While finishing his Master's degree in Geology at the University of California, Davis, Tyler Mackey traveled to Pavilion Lake to join the PLRP in 2010 as a research diver. Tyler is researching the microbialite formations to learn more about how signatures of microbial processes can enter the rock record.

"I'm particularly excited to join the PLRP crew because of the wide range of microbialite morphologies that are present here," wrote Tyler on the Pavilion Lake blog, June 30, 2010. Tyler's dives focused on a large microbialite structure that appears to be templating a boulder from a rockslide. "I'd love to see this in the rock record!" Tyler wrote, "There is always room for the unexpected in fieldwork, and I look forward to seeing what future dives will uncover in the lives of these microbial communities."

WHO

THE TEAM...

The Pavilion Lake team has grown from year to year, with more than 70 participants in 2010. They included researchers, visiting scientists, dive experts, communication and technical specialists, visiting teachers, graduate and undergraduate students, artists, and two cooks.

The research team consists of scientists specializing in a diverse range of fields, including Astrobiology, Biomechanics, Bioengineering, Chemistry, Education, Electrical Engineering, Environmental Fluid Mechanics, Geobiology, Geochemistry, Geology, Hydrogeology, Isotope Geochemistry, Limnology, Mechanical Engineering, Microbial Ecology, Mineralogy, Oceanography, Photosynthesis, Planetary Science, Planetary Virology, and Robotics.

About 20 members of the Pavilion Lake team are divers or DeepWorker scientist pilots. Since 2008, this group has included several astronauts, from both NASA and the Canadian Space Agency (CSA).

There are also a number of graduate and undergraduate students participating in the project. Several current scientist team members on the project began at the PLRP as graduate students.

In 2010, the PLRP started an Artist-in-Residence program that featured a Canadian sculptor. The intent of the program is to bring scientists and artists together to foster innovative problem solving. The 2011 field season will see the program grow with the addition of two more artists.

PARTNERS...

The main contributors to the PLRP are the CSA Canadian Analog Research Network program and the NASA Moon and Mars Analog Mission Activity program. Support from both these organizations made it possible for the PLRP to add a new communications trailer to their operations in 2009.

As the developer of DeepWorker submersibles, Nuytco Research is another important partner of the PLRP. Nuytco has provided the DeepWorkers to the PLRP every year since 2008, as well as training for operating the vehicles.[4]

Other partners include science organizations, such as the SETI Institute and the National Geographic Society, and numerous universities from around the world.

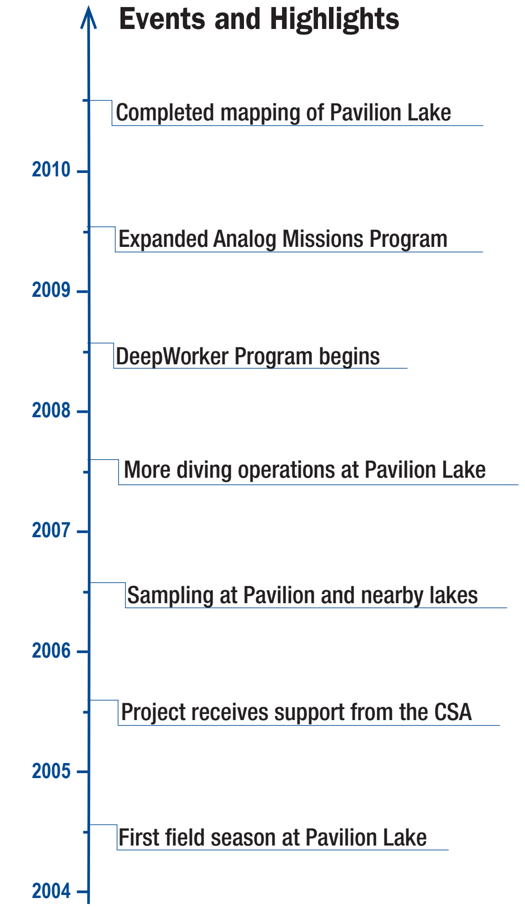
...AND YOU!

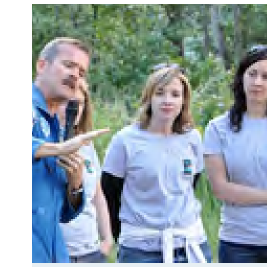
During PLRP missions, the exploration team reaches out to students, teachers, and the local Pavilion Lake community. Since 2008, the PLRP with the Spaceward Bound program have given several local teachers the opportunity to participate in the field activities at Pavilion Lake, working side-by-side with NASA scientists in hands-on research. During the 2011 field season, the PLRP team will partner with NASA, the CSA, and Google to deliver on-site Professional Development classes to teachers. This program is designed to benefit local students, as well, so that they may receive an education about human exploration from familiar teachers with real-life experience.

The PLRP also reaches students through live videoconferencing. Throughout the 2009 field season, the team engaged in live discussions with the Shad Valley student group in Vancouver. One of the astronauts at the PLRP also used videoconferencing to lead a live classroom activity with students from a local school.

The PLRP is also involved with the local community of Pavilion Lake. Every year, the team hosts a Community Day at Pavilion Lake, an open-house event for researchers and local residents to share their experiences. The PLRP team presents their research and explains their activities, while members of the community share their stories about the lake and its history. Every year the Pavilion Lake Community Day attracts more visitors and participants.

Of course, the PLRP team also reaches out to the general public. Using social media outlets like Wordpress, Picasa, YouTube, Twitter, and Facebook, the PLRP interacts with the public on multiple levels. Last year, the team provided daily updates on their field work, shared science reports, uploaded hundreds of photos, held photo caption contests, and shared stories about life and work at the PLRP on the site's blog, with contributions from several different members of the team, including the visiting teachers.





Partnership Success:
Teachers Make Great Students

The Spaceward Bound program, developed by NASA Ames Research Center, makes it possible for students and teachers to do hands-on research in real science expeditions. Since 2008, Spaceward Bound has partnered with the PLRP to host local teachers at the summer field tests, involving them in science research, mission planning, and outreach activities as soon as they arrive on site!

ISRU Fast Facts:

WHAT: Exploration technology development and prototype testing of ISRU systems in an international field project.

WHERE: Mauna Kea, a dormant volcano on the Big Island of Hawaii

WHEN: Two missions to date, in 2008 and 2010, and a third expected in 2012

WHO: Led by Bill Larson and Jerry Sanders of NASA, this team also includes participants from the Canadian Space Agency.

WHY: To advance technologies for sustaining human exploration on desolate planetary surfaces, by field testing those technologies at a site with characteristics similar to the Moon and Mars.

In-Situ Resource Utilization ISRU

When astronauts explored the Moon during the Apollo Program, they had to bring everything they needed to survive, including their oxygen and water, which limited their stays to just a few days. Longer stays require more resources, either from resupply launches or found on site. Because relying on resupply launches to provide the necessities for human survival is dangerous and costly, NASA wants to use technology that extracts or makes oxygen, water, rocket propellants, and building materials with the resources available on the lunar or planetary surface. Researchers from NASA's In-Situ Resource Utilization (ISRU) Project are developing mining equipment and production facilities to produce oxygen, water, and fuel in situ (on the planetary surface) as well as initial infrastructure for a base, such as a landing pad. To test these technologies, the ISRU team travels to the cold and dusty terrain of Mauna Kea, Hawaii.

The ISRU analog program has studied mining and production technologies and prototypes at Mauna Kea in two field studies. In 2008, the analog study brought together some important component technologies for the first time, and in 2010, the analog tested 17 different instruments and systems. This international project is hosted by Hawaii's Pacific International Space Center for Exploration Systems (PISCES), and includes the participation of the Canadian and German Space Agencies, as well as international universities and corporations. International participation is key to this project, because it allows for testing integration of hardware from different participants. Plans for operating these technologies in space will require seamless integration between partnered developers.

While the ability to produce oxygen from soil may be tested in the laboratory, these field tests at Mauna Kea are invaluable for testing system integration and effectiveness in harsh, dusty environments and mobility across rocky terrain with varied slopes.

WHERE

MAUNA KEA, HAWAII: DORMANT VOLCANO AND STAND-IN FOR THE LUNAR SURFACE

The dormant volcano of Mauna Kea on the Big Island of Hawaii has been an analog site since the Apollo era, when Apollo astronauts, scientists, and engineers used the site for geologic training sessions.[1] Then, as now, the site was chosen for its similarities to the lunar surface.

Cultural Awareness

Mauna Kea is considered sacred by native Hawaiians. To respectfully gain access to the site, the ISRU team cooperated with local people and had the site blessed by a Hawaiian priest.

Partnership Success:
Small Business in Space

We often hear of the large, traditional space companies like Lockheed Martin and Boeing producing hardware for space, but small businesses also played a major role in the Mauna Kea analog.

The 2nd International Hawaiian Analog provided opportunities for 14 small businesses from the U.S. and Canada to play a pivotal role in space exploration activities. These companies provided everything from science instrumentation for site characterization, to oxygen extraction modules, and solar concentrators.

The ISRU tests are located on the lower slope of the volcano, in an area resembling a lunar crater. This site offers terrain and rock distribution similar to lunar polar regions, well suited for testing ISRU operations.[2] The young volcanic material at Mauna Kea has high oxygen content similar to that found on the lunar surface, which makes it ideal for testing ISRU hardware. Another important feature of the site is the tephra, a fine, powdery material ejected during a volcanic eruption and an excellent simulant of lunar dust.[3] The high, dry altitude at Mauna Kea allows for testing of thermal energy systems, while the varied geological features provide multiple opportunities for testing science instruments.[4] Testing on Mauna Kea also provides its own logistical challenges. To make this analog happen, NASA has partnered with the U.S. Air Force Reserve to transport the equipment across the Pacific—an approximately 5,000-mile trip!

WHEN

PRODUCING OXYGEN FROM SOIL SINCE 2008

The first ISRU field tests were conducted in November 2008, followed by three weeks of testing in January 2010. The third international analog field test is scheduled for June 2012.[5]

WHY

EXPLORATION QUESTIONS ANSWERED

Helping to Make Space Exploration More Sustainable

The ISRU project seeks to improve human space exploration by advancing the ability to produce resources necessary for human life support, power, and propulsion from a planetary body, such as producing oxygen from the Moon's oxygen-rich soil. The ISRU team is also pursuing the ability to build infrastructure on a lunar or planetary surface.

Toward reaching these goals, the Mauna Kea analog study considered these key questions:

- Can we demonstrate the capability to prospect for water and resources that can be used to sustain, grow, and enable human exploration?
- Can we demonstrate the capability to extract and produce our own water, oxygen, and fuel from planetary rocks and atmospheres?
- Can we build critical infrastructure components out of in-situ materials, such as a landing site?
- Can products created from local resources be used in life support, power, and propulsion systems and how are their designs and operations changed?
- Can hardware and systems built by different universities, companies, and countries be connected together and operate efficiently?

The surface of the Moon contains an abundance of oxygen, so NASA and other international partners are developing systems to transform soil (also called regolith) into oxygen. However, to function on another planetary surface, this technology will need support from other kinds of systems, such as rovers, power systems, gas and cryogenic storage, and eventually propulsion systems. ISRU resource characterization plants, science instruments, and excavation devices will have to be integrated with rovers that prospect for and haul soil to the plant, all the while traveling over rocky terrain and operating in a harsh environment.

In 2008, the Mauna Kea team tested the Precursor ISRU Lunar Oxygen Testbed (PILOT) and ROxygen production systems with their prospective rovers. The Cratos rover, a small, tracked robotic excavator, hauls soil to the ROxygen plant, while a bucket drum device delivers soil to PILOT. The ROxygen plant completed three days of testing and conducted five complete reactor operations. The system demonstrated generating water from hydrogen reduction of Mauna Kea's volcanic soil (tephra). The PILOT system completed six full process runs and also generated significant amounts of water on each run, resulting in 1000ml of water through hydrogen reduction of the surrounding tephra. Together these systems can produce enough oxygen to sustain a crew of four on another planetary surface.[6] This was the first time ISRU systems were tested outside of the laboratory at a scale relevant to human exploration.

Another prototype system that was tested in 2008 was designed to determine how much water, hydrogen, and other volatiles exist in lunar polar regolith and at the same time produce oxygen from regolith, called the Regolith and Environment Science and Oxygen and Lunar Volatile Extraction (RESOLVE). RESOLVE was developed by NASA and included a drill developed in cooperation with the Canadian Space Agency (CSA) and a rover developed by Carnegie Mellon University. This small-scale system combines the four-wheeled Scarab drilling rover with RESOLVE to prospect the harsh lunar soil. At the Mauna Kea analog, Scarab travelled to four areas of the analog site, extracting a one-meter geologic core at each location. This core is then pulverized, and the crushed material is dropped into the RESOLVE unit for soil volatile characterization and oxygen extraction. The system was successful in characterizing gases and water in the soil, and it successfully generated water during a one-hour cycle. The primary purpose of core sampling for RESOLVE is to understand the depth and distribution of water ice in the lunar subsurface. The RESOLVE system may eventually be used to seek out water ice and volatile gases, such as hydrogen, ammonia, carbon monoxide, and helium, which could be used to produce fuels.

In 2010, a more integrated and higher efficiency system consisting of a regolith excavator, an oxygen extraction plant, a water electrolysis module, gaseous and cryogenic oxygen storage, a hydride hydrogen storage system, and a fuel cell demonstrated end-to-end production of oxygen from tephra and production of hydrogen for fuel cell operations. The excavator dug up and delivered the tephra to the oxygen extraction plant where the tephra was melted using concentrated sunlight and processed with methane to produce water. The water was then split into hydrogen and oxygen. The oxygen was successfully liquefied for storage, while the hydrogen was used to regenerate the system or in a fuel cell to power other experiments.[7] A total of 1600 grams of water was produced.

In 2010, the ISRU team also explored the question of whether we can build our own landing sites out of in-situ materials. Researchers tested equipment using TriDAR images and ground-penetrating radar to select sites for a landing pad and access roadways. A rover outfitted with a drill tested subsurface features, while other rovers equipped with blades plowed and leveled a simulated landing pad and road. The soil on the pad was sintered using two different methods, and thruster firings were performed to understand the effects of the plume on these surfaces. The results of the firing showed that while the pad mostly remained intact, in one area the top layer was removed from the bottom. The analog team determined that further work is required on sintering techniques.

Cratos rover approaching ROxygen plant

LESSONS LEARNED

Preparing for the Unexpected

Analog field testing of hardware and systems is vital to reducing the risk of systems failure in space, where problems will be much more difficult to solve. Engineers and scientists learn critical information from these tests to ensure successful integration, use, and long life in space. Often these analogs may reveal unexpected issues for further development.

During the 2008 field test, high winds kicked up volcanic dust at the site, creating a surprise analog for dust mitigation in hardware systems. Lunar dust is a major concern for lunar exploration, and any hardware used on the Moon will need to be protected. Dust mitigation techniques were used on some hardware and worked well during the test, but dust issues caused several resets of drilling electronics that were not properly protected. The team decided that dust mitigation techniques were a good opportunity for collaboration between NASA and new participants, to provide hardware with the environmental mitigation systems needed to survive in the dusty, rainy, cold analog environment.

Issues with system integration led to another lesson learned at the Mauna Kea analog. At the 2010 field test, NASA and CSA successfully integrated several hardware systems, however, the testing uncovered non-optimized power and fluid interfaces between elements that were developed separately. To avoid repeating these issues, future hardware tests will be designed to be more modular and require less assembly.

SUCCESSES

The Path to Sustainable Living off Earth

In-situ resource utilization has the potential to significantly reduce the risk and cost associated with sustained living on planetary surfaces. The 2008 analog

Fun Fact:

The oxygen used as the oxidizer for thruster firings was created in the Oxygen Extraction Plant during the analog.

RESOLVE drill on Scarab rover

successfully demonstrated end-to-end oxygen extraction from volcanic materials through the RESOLVE, ROxygen, and PILOT experiments. This analog also demonstrated the capability to detect water or ice in the soil using the Scarab rover on two nighttime traverses—an analog to detecting water or ice in permanently shadowed craters. A significant achievement of the 2008 demonstrations was perfect functioning of regolith-processing units despite surprise windstorms, which caused abnormally high concentrations of dust. Dusty conditions are a constant concern on the lunar surface, so this success was fortuitous.

The 2010 analog tested more systems than the first, but experienced equally exceptional results. Major results included successful tests for:

Rovers create pad and road

Site preparation: Successfully cleared and sintered two surface pads using two different sintering methods. The pads were then tested for thruster firings, which captured the effects of plumes on both the sintered and unmodified surfaces. It was found that melting or multiple layers must be used to survive the thruster plume.

Site characterization: Science Mission Directorate field science analog testing and Moon and Mars Analog Mission Activity instruments successfully characterized the soil composition at the site to support the oxygen extraction process.

RESOLVE system in a crater at Mauna Kea

Resource production: Successfully performed "Dust to Thrust" experiment, firing a thruster 12 times with oxygen produced from tephra. The team electrolyzed water from the surrounding tephra and fuel cells and transferred the oxygen to a cryogenic cart for liquefaction and storage. This team also successfully demonstrated advanced regolith transfer and processing hardware in an end-to-end configuration, by extracting oxygen from the tephra with an average yield of 9.6%.

Hardware integration: The NASA and CSA teams successfully integrated hardware developed at their respective agencies. Integrated systems include CSA rovers working with a NASA oxygen extraction plant, sintering devices, prospecting equipment, and German science instruments; CSA fuel cells powering NASA hardware; CSA devices integrated with a NASA solar concentrator for sintering; and CSA satellite and communications used for remote operations of NASA hardware.

Remote operations: Four systems were successfully operated remotely from NASA centers on the mainland. The RESOLVE system was operated from NASA Kennedy Space Center, while the solar collector, carbothermal reactor, and water electrolysis systems were operated from NASA Johnson Space Center.

WHAT

TESTING EQUIPMENT AND SYSTEMS FOR SPACE RESOURCE UTILIZATION

The first Hawaiian ISRU field test focused on three oxygen production plants—PILOT, ROxygen, and RESOLVE—along with respective rovers, drills, and spectrometers for studying the soil. Most of the equipment was being tested outside the laboratory for the first time, and it was also the first time that all these systems were integrated for operation before testing.

The second field test, in 2010, continued this theme, further testing equipment and systems for the Space Resource Utilization Operation Cycle. This cycle includes resource identification and planning, site preparation, mining, crushing and sizing, processing, and product use and storage. This analog specifically studied enhanced oxygen extraction from regolith, ISRU product storage and utilization, integrating exploration and science data, site preparation, and geology training.[8] Tested systems include 8 system modules and 7 instruments from NASA, as well as 12 system modules and attachments from CSA.

NASA systems and instruments included:

Site and Resource Exploration Technologies: These systems include the RESOLVE drill and seven different instruments used for imaging, sampling, and analyzing the surface. Results of these exploratory activities help determine the best sites for access roads and launching pad demonstrations.

Site Preparation and Excavation Technologies: The Mauna Kea analog evaluated site excavation activities using rovers outfitted with lift-haul-dump blades and plows for excavating, moving, and preparing soil. They further evaluated soil sintering using concentrated solar energy and resistive heating methods. These systems are used to create access roads and simulated landing pads.

Oxygen Extraction Technologies: These systems demonstrated NASA's capability to produce oxygen from a site's native soil, the tephra at Mauna Kea. The evaluated technologies included rovers that delivered regolith, the carbothermal reduction system, and the end-to-end integration of these systems.

Energy Technologies: These technologies, which included a solar concentrator and fuel cell power systems, were evaluated at Mauna Kea as power systems for extraction activities, allowing the team to reduce the use of gasoline electric generators.

Production, Storage and Utilization Technologies: This field test evaluated technologies for liquefying the produced oxygen and storing it for use in fuel cells and other systems. Specific systems included a liquid oxygen/methane tank, cryocooler cart, and hydrogen hydride tanks.

CSA tested imaging and data analysis tools, multiple rovers with accompanying plow and excavation attachments, an autonomous regolith delivery system, a device to control solar sintering, and a mining vehicle fuel cell.

WHO

THE TEAM...

The Hawaiian analog is an international team consisting of members from 6 NASA centers, CSA, the German Space Agency (DLR), 14 small businesses from the U.S. and Canada, and 7 universities. Together, the groups from both missions total nearly 100 personnel. Bill Larson and Jerry Sanders, NASA in-situ resource utilization project leads, lead this analog study.

THE PARTNERS...

The Mauna Kea analog is truly an international field test. Partners in these activities include international space agencies, other government organizations and laboratories, international universities, and the commercial industry. The Mauna Kea test site itself is operated by PISCES, which partners with NASA to host the analog activities.

International partners include the CSA, the Natural Resources Canada, Communications Research Center (Canada), and the Northern Centre for Advanced Technology, whose participation has grown significantly since the first field test. Additionally, the DLR and University of Mainz in Germany contributed equipment and personnel to the analog.

Several commercial industry partners like Lockheed Martin, Honeywell, and Michelin North America also participated in the analogs, providing rovers, drills, instruments and even custom wheels.

...AND YOU!

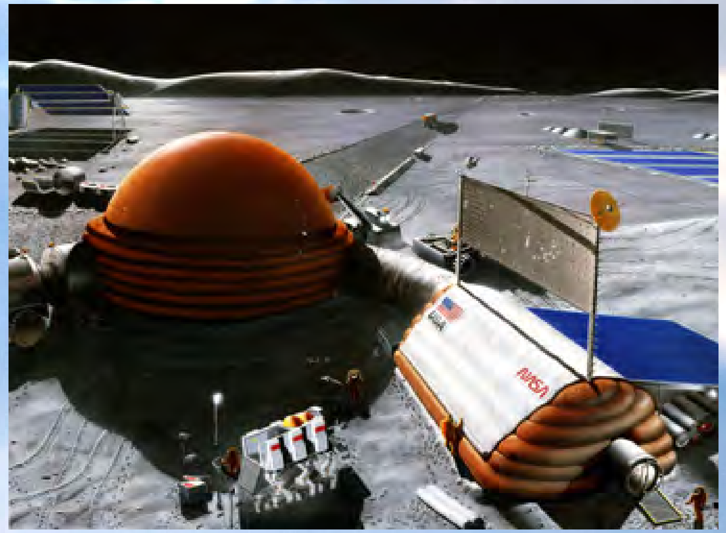
The ISRU field test team engaged students and the general public through live school presentations, student involvement, traditional media, and social media. Representatives from NASA, PISCES, and DLR gave presentations to local middle and intermediate school students, as well as to Civil Air Patrol cadets. Some students had the unique opportunity of being directly involved in the study. One geology student participated in thruster impingement efforts, while nursing and culinary students provided supporting roles in the activity. A media day event was held with the participation of about 25 news crews, including one from South Korea. Finally, the analog updated followers of its activities on a Twitter account and through a video feed on the test site.

Team Member Cross-Over:

Bekah Shepard

Bekah Shepard is a researcher assigned to the Pavilion Lake Research Project. She has contributed to both the Desert RATS and Mauna Kea ISRU analogs. Bekah has developed metrics for assessing science operations and field work. She and her colleagues have developed "tools for evaluating how successful we are at doing research." Through her work at different analog sites she feels, "We are gaining a better and better understanding of how science functions in each of these types of analogs, and that helps us all to become better exploration scientists."

Inflatable Lunar Habitat Analog Study
Antarctic Habitats



Antarctic Analog Mission Fast Facts:

WHAT: Testing an inflatable habitat by operating it for one year in an extreme environment.

WHERE: McMurdo Station, Antarctica (77° 51' S, 166° 40' E)

WHEN: January 2008 through February 2009.

WHO: NASA, NSF, and ILC Dover. Led by Larry Toups, Habitation Systems Lead, NASA Johnson Space Center.

WHY: Antarctica is an extreme and remote environment, presenting challenges to the habitat that are not present in a lab. This helps scientists and engineers gain a new perspective on design.

Fast Facts: The Habitat

- A tubular inflatable structure consisting of two areas: the main habitation area and the simulated airlock
- 16 feet (4.9 m) wide by 24 feet (7.3 m) long, with a total of 384 square feet (36.7 square meters)
- Weighs 950 pounds, less than half the 1-ton tents of the same size at McMurdo Station
- 19 inch (48.3 cm) thick walls when inflated
- Maximum headroom of 8 feet (2.4 m) at the center of the curved ceiling
- Can be deployed in 50 minutes by a three-person crew
- Can be taken down and reused
- Built to withstand over 100 mph winds
- Outfitted with an insulation blanket, guy wires, power and lighting systems, a pressurizing system, heaters, a protective floor, and sensors to monitor the structure and environment

Photo courtesy of Aeon Jones www.thejonesz.us

One of the major goals of space exploration is to someday have humans living and exploring safely on planetary bodies, like the Moon or Mars, for long periods of time. People living on these distant planetary bodies will need some kind of habitat in which to live. To achieve this goal, astronauts must have a reliable habitat to protect them from dangers like extreme temperatures, radiation, lack of an atmosphere, and the overall remoteness of these harsh environments.

One promising approach to the challenge of creating such a habitat is the concept of inflatable structures. These habitats look like large, enclosed moon bounces, but are much stronger and more rigid when inflated. The main advantage of inflatable structures is that you can launch them deflated, so they weigh less and take up less volume at launch. This is much more cost-effective than launching traditional building materials or pre-built structures. Another advantage is that these structures are comparatively easy to deploy. They simply need to be anchored to the ground and then inflated. An inflatable structure might even be reusable, so an astronaut could deflate it, pack it up, move to a new location, and then re-inflate it.

Any system operating in a space environment has many challenging operational requirements, such as the ability to use power efficiently, to operate reliably with minimal human intervention, and to withstand environmental conditions such as temperature extremes, micrometeorites, and harmful radiation doses. To test performance in these areas, designers and engineers often look for extreme environments on Earth that are analogous to space environments. For the inflatable habitat, NASA decided that the extreme environment of Antarctica presented an excellent opportunity to test the performance of a prototype inflatable structure.

National Science Foundation (NSF) and ILC Dover's prototype inflatable structure

WHAT

TESTING AN INFLATABLE HABITAT

Pursuing the concept of inflatable habitats, NASA partnered with the National Science Foundation (NSF) and ILC Dover to build a prototype of an inflatable structure and deploy it in the harsh environment of Antarctica for one year. Eight team members spent 10 days at McMurdo Station to deploy the habitat, install the monitoring systems, and run initial tests. The habitat remained deployed for the rest of the year, and its performance was monitored remotely.

This yearlong test helped engineers and scientists evaluate how well the concept of an inflatable structure addresses all of the challenges and requirements of exploration habitats. It also helped the NSF assess the applicability of inflatable structures to their polar missions. NASA engineers will use the lessons learned from the experience to inform and improve future designs.

McMurdo Station

WHERE & WHEN

JANUARY 2008 TO FEBRUARY 2009, McMURDO STATION, ANTARCTICA

The environmental extremes found in Antarctica make it a valuable location for analog studies. It is the driest, coldest, highest, windiest, and brightest continent on Earth and one of the most remote places in the world. This isolation constrains operations and communications, which means that the team needs to plan carefully, because if anything goes wrong, it is much more difficult to fix.

NASA conducted this study from January 2008 through February 2009 at McMurdo Station in Antarctica. McMurdo Station is a permanent facility located on Ross Island and serves as the NSF's logistics hub in Antarctica. The station was built in 1955 and sits on an area of bare volcanic rock jutting from the island. The station consists of 85 buildings, a harbor, a landing strip, and a helicopter pad. Scientific research is conducted at the station year-round.

At McMurdo Station the mean annual temperature is -18°C (0°F) with seasonal extremes ranging from 8°C (46°F) in summer and -50°C (-58°F) in winter. Average wind speed is 12 knots (14 mph), with extremes exceeding 100 knots (115 mph).

Antarctica is not a perfect analog for the Moon or Mars. However, like the Moon and Mars, it is an extreme environment and remote location, and therefore it presents more challenges than a NASA field center. The challenges presented by the Antarctica location help uncover weakness or flaws in the design, so that scientists and engineers might think differently about the demands that will be placed on the structure and the people living there.

WHY

EXPLORATION QUESTIONS ANSWERED

On Habitat Performance and Potential

Going into this analog study, the team had a number of questions about inflatable habitats that they hoped to answer:

- Could a system like this be easily deployed by people with limited mobility? Low gravity and bulky spacesuits make even simple tasks difficult and strenuous.
- Could a system like this be easily repacked? The ability to repack a habitat, move it, and redeploy it elsewhere could be valuable to space explorers.
- Could a system like this operate efficiently in terms of heating? Could the inflatable walls provide sufficient insulation? Planetary bodies like the Moon and Mars can be extremely cold and power supplies would likely be limited, so it would be important for such a habitat to retain heat well.
- Could a system like this be resilient enough to stand up to extreme cold, dust, and wind for an extended period of time? An inflatable habitat would need to reliably withstand harsh environments on planetary bodies.

In general, the team was pleased with how the habitat performed during the test. They demonstrated complete setup and takedown several times in the first week of the study and found that the process took only 50 minutes when carried out by a three-person team. In fact, the inflation and deflation steps took only six minutes each. Because the team had to wear cumbersome extreme cold weather gear during setup and takedown, they gained some insight into the types of challenges astronauts will face wearing spacesuits.

The team used a system of sensors to monitor temperature, pressure, power consumption, air flow, and air quality within the habitat. Sensors outside the habitat monitored external temperature, wind, and light intensity so that the team could analyze how external conditions affected the interior of the habitat. These sensors were placed in many locations, including under the floor and even under the ground beneath the habitat.

The sensor system detected no major problems with heat leaks, although it did detect subtle differences in parts of the habitat where the insulation had been compressed. The habitat successfully withstood months of high wind up to 50 knots (58 mph) and temperatures as low as -59°C (-75°F).[7]

LESSONS LEARNED

To Build a Better Habitat

The yearlong experiment led to several lessons learned that will affect future inflatable habitat designs. The team learned that future inflatable habitats need a higher level of autonomy. Throughout the yearlong experiment, the habitat experienced several problems that required manual human intervention. This type of intervention might not be possible on the surface of the Moon or Mars, especially if the habitat is unattended for any length of time. The team determined that a usable inflatable habitat will need to have more autonomous maintenance capabilities so that it can resolve problems like these without manual intervention. The team also gained a year's worth of experience monitoring the habitat and responding to off-nominal sensor readings by devising tests and implementing solutions. This helped them gain a better understanding of the level of support that a habitat requires.

Complete setup took an average of 50 minutes, while inflation and deflation steps took up only 6 of those 50 minutes

During setup, the team experienced some challenges in integrating all of their sensors, because the sensors were not standardized. Careful planning and testing was required to ensure that none of the sensors interfered with another. To reduce this burden, the team recommended that future inflatable habitats integrate embedded sensors into a standardized wireless network. This has the added benefit of reducing wiring inside the habitat.

The team also faced some challenges during setup that are unique to an inflatable habitat. For example, when trying to install a rotating camera to the ceiling of the habitat, the team discovered that the ceiling was not rigid enough to hold the base of the instrument steady as the camera turned. The team was able to develop a work-around solution, but this is an example of the unique challenges presented by inflatable habitats. The team also learned that they need a better way to fasten things to the walls of inflatable structures, as traditional methods such as nails and screws are not an option with inflated walls. In Antarctica, the team used a network of cords and Velcro straps to install sensors and other equipment. However, the team recommends using wireless sensors as much as possible, because these can be sewn into pouches on the habitat's walls or affixed using adhesive, thereby bypassing the need for cords and straps. Another advantage to this approach is that wireless sensors can be installed pre-inflation, which simplifies deployment and makes ladders unnecessary.

SUCCESS
Of a Livable Habitat

The Habitat was well equipped with sensors and other devices to collect data on its performance, but to test the human experience of living in the habitat, the team slept in the habitat overnight. The team added lightweight, interlocking foam squares to the floor of the habitat and slept in sleeping bags for one night of their stay. The habitat protected the team members from the harsh Antarctic night, and the team reported that the habitat was very livable.

WHO
THE TEAM...

An eight-person team visited Antarctica for 10 days in January 2008 to deploy and test the habitat. The team included four engineers from NASA Johnson Space Center (JSC), including project lead Larry Toups and Habitat project manager Gerard Valle. The team also included two ILC Dover engineers and two researchers from the NSF Raytheon Polar Services. A ground control team at NASA JSC monitored the habitat's performance for the rest of the year, until February 2009.

PARTNERS...

This analog study was conducted by three partners: NASA, the NSF, and ILC Dover of Frederica, Delaware. The NSF has similar interests to NASA, because they too send teams of people to explore and conduct science experiments in remote and harsh environments. Just like NASA, the NSF could benefit greatly from a habitat that is low in mass; easy to pack, transport, and deploy; and durable enough to withstand harsh environments and multiple uses. Because of this shared interest, NASA and NSF partnered to conduct this analog study. ILC Dover was chosen to build the habitat because they have considerable experience building inflatable structures and other space-rated systems. ILC Dover built the structure, NASA built and provided the data system responsible for monitoring and communication, and the NSF provided transportation, setup, and on-site support at McMurdo Station. The three partners shared all findings and results.

To make the study as useful as possible to NSF, ILC Dover designed the inflatable habitat prototype to be similar in size and shape to the conventional cold-weather NSF housing structure, called a Jamesway hut. A Jamesway hut is portable and relatively easy to assemble, and it consists of a wood frame and an insulated cloth cover. NASA installed monitoring systems on several operational Jamesway huts at McMurdo Station, allowing the team to compare performance of the inflatable habitat with the performance of the Jamesway huts. This helped NASA understand how the performance of an inflatable structure compared to a rigid structure. It also helped NSF understand what types of performance benefits they might expect if they transitioned to using inflatable habitats in the field. The performance of the inflatable prototype fared very well compared to the Jamesway hut. In addition to providing an easier means of deployment in a shorter period of time, the inflatable structure tended to maintain a warmer interior environment than the Jamesway hut.

...AND YOU!

NASA and its partners have engaged the public in this analog study in a number of ways, ranging from student contests to social media. In fall of 2008, the "Name that Habitat" contest invited students from 6th through 10th grade to submit a name for the inflatable habitat. In January of 2009, the ninth-grade class of Holy Cross High School in Delran, New Jersey, won the contest for their entry, "Resolution," named after Captain James Cook's 1773 exploration vessel, which was the first ship to cross the Antarctic circle. The team also created a blog to record their experiences traveling to McMurdo Station and beginning the study. The blog contains a number of useful links to other resources: http://www.nasa.gov/exploration/analogs/inflatable_habitat_blog.html

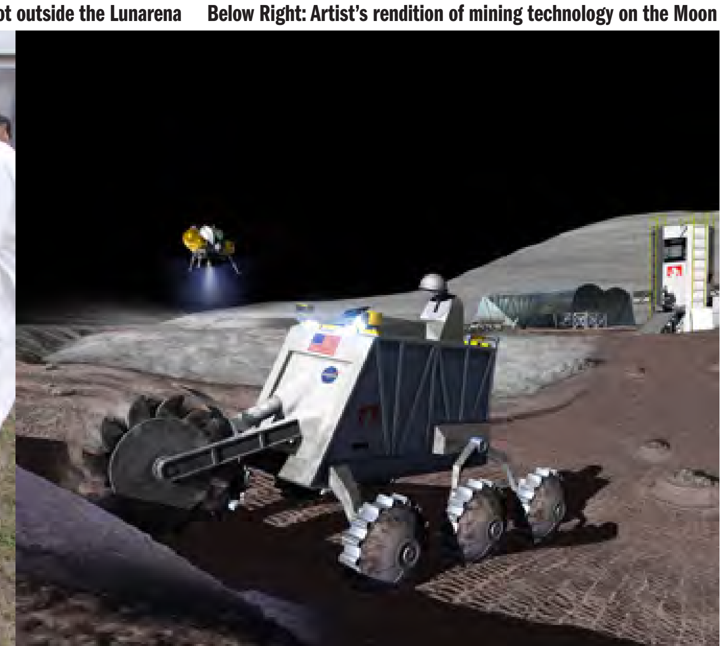
NASA and its partners have provided a way for the public to explore Antarctica and get a feel for the extreme environment from the comfort of their own homes. The NSF provides a live video feed of McMurdo Station via Webcam, positioned to look out over the station and the water further south, giving a good view of oncoming storms. The Website also displays current weather conditions at the station as well as information about all of the current research projects being conducted at the station. The Webcam may be accessed by following this link: http://www.usap.gov/videoClipsAndMaps/mcmwebcam.cfm

Through a project called LIMA (Landsat Image Mosaic of Antarctica), NASA has made available online a high-resolution satellite image mosaic that allows members of the public to explore the Antarctic terrain around McMurdo Station from a bird's eye view. The imagery is available as individual frames or as videos, some of which include narration and even labels on important landmarks. This imagery was produced jointly by NASA, the NSF, the U.S. Geological Survey (USGS), and the British Antarctic Survey (BAS) and is available online by following these links: Video: http://lima.nasa.gov/mcmurdo/. All imagery: http://svs.gsfc.nasa.gov/vis/a000000/a003400/a003482/.

The team's motto for the Habitat Study: "Packs like a tent, acts like a building"

Please see the Public Engagement section of this report for more information about public outreach and NASA analog studies.

Above: Lunabot preparations in the Astronaut Hall of Fame   Below Left: Preparing a Lunabot outside the Lunarena   Below Right: Artist's rendition of mining technology on the Moon



Public Engagement & Education

Students doing simulations of telesurgery with NEEMO 12 and the University of Cincinnati.

One of the key missions of NASA is to reach out and inspire the public about the possibilities of exploring space. Because the analog missions test operations, science, and technologies for space exploration here on Earth, they grant the public an unparalleled opportunity to closely engage with exploration activities and provide a unique education experience to students of all ages.

Public engagement is a tool for teaching the public about how exploration studies impact their lives, while participatory exploration allows the public to contribute to and collaborate with the exploration team, providing real inputs into real exploration activities. Education is a critical part of outreach activities, because the space explorers of the future will be found among today's young adults. Analog missions provide opportunities to engage and involve students, inciting an appreciation for the science, technology, engineering, and math disciplines among these future explorers. This chapter describes how every analog study uses new and creative ways to engage and educate the public, and how readers can become involved in future analog missions.

Public Engagement

An analog is a unique laboratory setting. Instead of sterilized white-walled-rooms and labcoats, you see spacesuits on a Mars-like desert or diving suits on the ocean floor. Because these unique settings are chosen for their similarities to the space environment, analog tests make it easy for both scientists and the general public to visualize how technologies will be used and operations will be conducted in space. By taking studies outside the lab, analogs provide a special opportunity for the public and NASA scientists to learn new information about space exploration. People across the world can even become "citizen scientists" and contribute to real experiments through participatory exploration activities.

Media

Analog studies are devoted to sharing their experiences with an unlimited audience, using a variety of media outlets. Everything from traditional media—such as news releases, journalism, and television spots—to daily updates on social media applications—such as Twitter, Facebook, and Flickr—helps analog researchers reach out from their remote locations to engage with a worldwide audience.

Social Media

Social media applications are enabling analog scientists to reach the public in real time to share their daily activities and findings. Public audiences are taking advantage of this new communications channel, with thousands of followers on Twitter, fans on Facebook, and hundreds of thousands of YouTube views. The public is actively engaged in ongoing dialogues with analog mission teams through these channels, exchanging questions and answers as the mission happens. For example, on the NEEMO and Desert RATS Facebook pages, analog researchers and Facebook users engage in constant conversation, often receiving responses from each other within the hour. Each of the six analogs in this report use blogs, Facebook, Twitter, or all of the above to provide the public with daily updates during each mission. Links to these sites are in provided below.

Of course, one of the most exciting ways to connect with and inspire the public is to let the public see what an analog is, not just read about it. With hundreds of photos available on photo-sharing sites like Flickr and Picasa, people can see every detail of what goes into an analog study: advanced technology in action, the many members of the team, behind-the-scenes operations supporting the field test, and the vast landscapes or blue underwater surroundings of the site itself.

Links to each analog's social media site

Social Media	Analog	Link
Blog/ Main Page	Antarctica	http://www.nasa.gov/exploration/analogs/inflatable_habitat_blog.html
	Desert RATS	http://blogs.nasa.gov/cm/newui/blog/viewpostlist.jsp?blogname= analogsfie ldtesting
	HMP	http://www.marsonearth.org/
	Mauna Kea, ISRU	http://www.nasa.gov/centers/kennedy/moonandmars/hawaii_testing.html
	NEEMO	http://blogs.nasa.gov/cm/newui/blog/viewpostlist.sp?blogname=analogsfiel dtesting
	Pavilion Lake	http://www.pavilionlake.com/blog/
Twitter	Desert RATS	http://twitter.com/DESERT_RATS
	HMP	http://twitter.com/HMP
	NEEMO	http://twitter.com/NASA_NEEMO
	Pavilion Lake	http://twitter.com/PavilionLake
Facebook	Desert RATS	http://www.facebook.com/pavilion.lake#!/pages/NASA-Desert-RATS/ 122098681161930
	HMP	http://www.facebook.com/group.php?gid=19183292384
	NEEMO	http://www.facebook.com/pages/NASA-NEEMO/120100478009378
	Pavilion Lake	http://www.facebook.com/pavilion.lake
YouTube	HMP Research Station	http://www.youtube.com/user/HMPResearchStation
	NASA Analog TV (includes videos from multiple analogs)	http://www.youtube.com/user/NASAanalogTV
	Pavilion Lake Blog	http://www.youtube.com/user/pavilionlakeblog
Flickr	Desert RATS	http://www.flickr.com/photos/nasadesertrats/
	HMP	http://www.flickr.com/photos/hmpresearchstation/
	NEEMO (in NASA Analogs' photostream)	http://www.flickr.com/photos/40054892@N06/sets/72157623997951074/
	Pavilion Lake (in NASA Analogs' photostream)	http://www.flickr.com/photos/40054892@N06/sets/72157624201875441/
Picasa	Pavilion Lake	http://picasaweb.google.com/pavilion.lake
GigaPan	Desert RATS	http://www.gigapan.org/profiles/27956/

Videos do an even better job of sharing the activities of an analog mission with public audiences. Analog teams upload videos of their operations on their blog or on YouTube so the videos are free and easy to access. These videos can include interviews with individual participants of the analog study, show how a technology or operations concept is tested, or even provide live webcam monitoring of the site. These videos allow a person to be as close to the analog site as possible without actually being there. Given that most of these analogs are in extreme environments, that might even be preferable!

Traditional Media

While social media outlets are great for communicating with people already aware of analogs, traditional media outlets can share the analog story with a wider audience. The analog teams reach out to national and local media, by issuing press releases, supporting interview requests, and hosting media days. Coverage in traditional media lets the general public follow what NASA is doing to prepare for future exploration missions while also drawing in new virtual explorers and fans.

The following is a sample of some of the major newspapers, magazines, science journals, and television shows that have featured at least one analog study:

- The Boston Globe
- Chicago Tribune
- The New York Times
- The Washington Post
- CBS SmartPlanet
- Fortune
- Trendhunter Magazine
- CNN Tech
- IEEE Spectrum
- National Geographic
- Popular Science
- Science World
- Daily Planet, on Discovery Channel Canada
- Storm Worlds, on National Geographic Channel

Twitter Followers	
Desert RATS	9,462
HMP	562
NEEMO	1,864
Pavilion Lake	291
Facebook Page Likes	
Desert RATS	1,289
NEEMO	1,124
Pavilion Lake	309
Facebook Group Members	
HMP	310
YouTube Views	
HMPResearchStation	53,948
NASAanalogTV	170,169
Pavilionlakeblog	6,129
YouTube Subscribers	
HMPResearchStation	92
NASAanalogTV	11,153
Pavilionlakeblog	19
Flickr Views (average per album)	
Desert RATS	2,430
HMP	4,356
NEEMO (in NASA Analogs)	5,194
Pavilion Lake (in NASA Analogs)	210
Picasa Views (average per album)	
Pavilion Lake	1,991

Numbers of social media views and visitors as of March 2011

Some media is generated on a smaller, but no less important, scale. Pavilion Lake hosts an annual outreach event for the community. Every year on "Community Day," the local residents of Pavilion Lake are invited to meet the research team, hear presentations about the exploration activities, and ask questions about the science conducted at the analog site. Last year, over 100 people attended the event.

Some media is in an entirely different genre altogether. On their Northwest Passage Expedition to deliver the Moon-1 Humvee Rover to Devon Island, Haughton-Mars Project (HMP) researchers were accompanied by a film crew from Jules Verne Films & Expeditions. Award-winning director J. C. Jeauffre filmed the record-breaking arctic voyage for his upcoming 3D documentary, Passage to Mars. The movie is currently in production.

Participatory Exploration

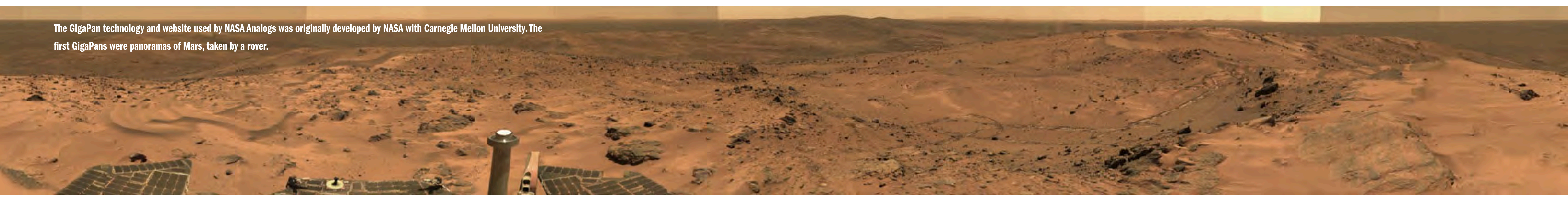
Analog participants know that the only thing better than learning about analog activities and watching them as they happen is being involved in the activities yourself. That is why analog studies offer participatory exploration opportunities—so that anyone anywhere can experience and contribute to the advancement of exploration.

GigaPan: A Picture is Worth a Thousand Pictures

Viewing a GigaPan image is an act of exploration in itself. GigaPans are made of multiple photographs seamlessly stitched together, creating one large, high-fidelity panorama. The minimum size of a GigaPan is 50 megapixels (50 million pixels) and the largest GigaPans are multiple gigapixels (one gigapixel=1 billion pixels). This amazing resolution allows a viewer to see a broad picture of a site and then zoom in on minute details, visible in clear focus. For example, a user can look at a fantastically vast and clear picture of the Grand Canyon and then zoom in to inspect the details of a single rock. If a viewer finds an interesting detail, he can take a snapshot of the image, which is labeled and saved on the GigaPan's webpage, so other users can zoom in on the same piece of the GigaPan. GigaPans are uploaded and shared on gigapan.org, which is free to join, so anyone can view and comment on photos, take snapshots, and comment on snapshots taken by others. This means that analog researchers can create GigaPans of an analog site, and anyone in the world can virtually explore the site with them.

There are 29 Desert RATS GigaPans online, offering different opportunities for participatory exploration. Anyone can become a "citizen scientist," collaborating with the Desert RATS scientists and other citizen scientists, by taking snapshots of interesting geology and commenting on the features. Many comments spark conversations between users, like discussions of which areas would make good candidates for EVA stops and why. In another participatory exploration activity, these users had the real opportunity to decide where the astronauts would go on their next traverse.

What goes around, comes around. . .



The GigaPan technology and website used by NASA Analogs was originally developed by NASA with Carnegie Mellon University. The first GigaPans were panoramas of Mars, taken by a rover.

Using six snapshots from two GigaPan images, Desert RATS researchers invited the public to choose a site of geologic interest where the rover teams could explore. More than 2,500 people from 88 countries submitted votes, and the majority voted for location F, a point of multiple overlapping lava flows. Without even visiting the field site in person, thousands of people from all over the world were able to contribute to the analog's exploration activities.

MAPPER: Underwater Exploration on your Desktop

The Pavilion Lake Research Project (PLRP) has amassed tens of thousands of video images of microbialites, and someone has to go through every photo to classify each structure in specific detail. Because the classification system is subjective (Does that look bulbous to you? Or is it cylindrical?), every photo needs to be reviewed multiple times. If they depend on only a handful of PLRP researchers with the tools and knowledge to do this task, it could take a while.

Fortunately, someone at the PLRP came up with a solution that provides more help to do the science while also reaching out to the public: MAPPER (Morphology Analysis Project for Participatory Exploration and Research). MAPPER is a web-based version of the microbialite classification system, with a graphical user interface that is easy to use and can be learned quickly. MAPPER is currently limited to use at the PLRP, but its developer, Nick Wilkinson, is working on a version of the software for the general public. Once it becomes available, anyone can help classify the microbialite images, by downloading the software and photos onto their computer. After classifying an image, users will return the data to the PLRP, where the information will be added to a huge database. PLRP scientists can then run queries in the database, to find correlations between different features of microbialites. With the help of thousands of willing citizen scientists, researchers at the PLRP will be able to process their huge collection of images and may finally learn how and why these strange underwater structures are formed.

Education

Analog missions provide an excellent opportunity to energize scientific interest and spark wonder in

Citizen Scientist = Someone who volunteers remotely to monitor and/or provide data to NASA science. Thousands of objects, including nebulas and supernovas, were discovered by citizen scientists.

The white frame is the snapshot of the winning "location F. If you were online, you could zoom in on that tiny box and clearly see the individual rocks in the lava flow.

students, from elementary to graduate schools. Through live lessons, contests, and other interaction, analog participants find creative ways not just to teach students but also to involve them in the excitement of scientific discovery.

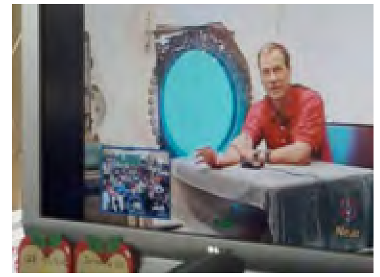
Live Lessons and School Participation

Most analogs are conducted in extreme environments, making it impractical to host a group of young students. Live webcasts and videoconferencing allow analog researchers to bring their exploration activities into a classroom or to many classrooms at once. In 2007, astronauts and astrobiologists at the HMP interacted with students from twelve participating Challenger Learning Centers across the United States. Their five webcasts included discussions about living in a remote base camp and how to test spacesuits, and allowed students to ask questions of the analog teams. Since 2006, the NASA Digital Learning Network (DLN) has presented webcasts to about 30 schools around the country, from the Desert RATS field site and also from the underwater habitat of the NEEMO missions.

Microbialite formations in Pavilion Lake

Some analog researchers have participated in school activities in person. During their ISRU studies at Mauna Kea, the team traveled to Hawaiian schools and the Civil Air Patrol to teach students about the exploration activities happening in their home state. In San Anselmo, CA, HMP director Dr. Pascal Lee makes frequent visits to Sir Francis Drake High School to teach students about Mars and human exploration. Dr. Lee made a special appearance with the Moon-1 Humvee Rover before he drove the vehicle across the Northwest Passage to Devon Island. "I hope (Drake students) realize that science and learning can be fun, and that you can make a living working in science," says Lee.

Participatory Exploration



Astronaut and aquanaut Tom Marshburn speaks to hundreds of children in a live webcast during NEEMO 14.

There is no better way to educate our future explorers than to involve them in science as it happens. Participatory exploration is used in an educational setting to give students and their teachers the chance to virtually contribute to space exploration research and to better understand the challenges and excitement of doing real science and advancing real-world technologies. For older students, the opportunity to experience exploration and discovery firsthand is made possible with competitive internships and interactive activities.

Student Contests

College students from across the country compete for chances to participate in actual Desert RATS missions each year. There are several NASA contests for undergraduate and graduate students to participate in this analog mission.

The Moon Work Engineering Design Challenge is open to any college student with a technology idea to improve lunar exploration. (In 2011, the focus was broadened to space exploration, and the name of the program was changed to SpaceTech Engineering Design Challenge.) The technology design categories include a wide range of engineering challenges, from autonomous robotics to propulsion technologies. The winner of the best technology design receives a paid internship to NASA's Exploration Technology Development Program and a trip to Arizona for a Desert RATS mission. Last year's winning interns got to ride in one of the rovers to assist the crew and also worked on the wiring of a Shirtsleeve EVA Backpack. This unique opportunity let them experience the benefits of scientific and technology discovery firsthand.

Since its announcement in 2009, the Lunabotics Mining Competition challenges student teams to build the best autonomous mining technology for use on the Moon. Whichever team mines the most regolith in the allotted time wins a cash prize, and they have a chance to also win a special award for a trip to a Desert RATS mission. Excavating on the Moon poses many challenges, such as the unique nature of Lunar regolith, the vacuum environment, and reduced gravity. The contest recreates these challenges as closely as possible—for example, teams are not allowed to use hydraulics, because hydraulic fluids will either freeze or boil in the Moon's extreme environment. In 2010, the team from Montana State University won both the overall prize and the Desert RATS trip with their excavator, M.U.L.E. Their success may advance human exploration technologies and inspire innovative thinking among other students and engineers.

In addition to the two annual competitions directly tied to Desert RATS, other NASA competitions provide opportunities for university students to contribute to the analog mission. In 2010, the Revolutionary Aerospace Systems Concepts-Academic Linkage (RASC-AL) program provided an opportunity for participation in Desert RATS. RASC-AL is an annual design project competition sponsored by NASA and the National Institute of Aerospace for university-level engineering students. The competition brings together students to compete on developing technologies to address exploration challenges, with specific exploration themes each year. The 2010 first and second place undergraduate teams won trips to travel to Desert RATS to observe the analog mission and test the winning RAVEN (Robotic Assist Vehicle for Extraterrestrial Navigation) rover developed by the University of Maryland/Arizona State University team. In 2011, the X-Hab Academic Innovation Competition will provide an opportunity to university teams to compete head-to-head in the design and demonstration of an inflatable habitat "loft" which will attach to the Habitat Demonstration Unit (HDU)

Virtual Exploration, Real Education

The NASA eEducation Island, sponsored by NASA Learning Technologies, is an education project located in the virtual world of Second Life. On NASA eEducation Island, your avatar (a personal character that represents you in the virtual world) can study spacecraft, search for meteorites, or explore analog missions, including Desert RATS and NEEMO. Sometimes analogs host mixed reality events, such as streaming a live webcast into Second Life and engaging in discussions with virtual participants. Second Life is free to join, for anyone 18 or older.

Teacher AnnMarie Byrnes and the Honors English I class at Holy Cross High School in Delran, N.J. submitted the winning entry "Resolution" for the NASA/Challenger Center competition to name NASA's inflatable Antarctic habitat.

Student doing a simulation of telesurgery with NEEMO 12 and the University of Cincinnati

forming a second floor. Concepts have to self deploy, be able to be installed on NASA's HDU, and meet mass and volume constraints. University teams from Oklahoma State, Wisconsin, and Maryland were chosen to participate in the 2011 head-to-head competition. The winning team gets funding to further develop their design and to participate in field testing of the "loft" at the 2011 Desert RATS mission.

Of course, not all the analog contests are limited to college students. In the fall of 2008, students in the 6th through 10th grades participated in a contest to name the inflatable habitat in the Antarctic analog. The "Name that Habitat" competition ended in January 2009, when the ninth-grade class of Holy Cross High School in Delran, NJ won the contest for their entry, "Resolution." It was named after Captain James Cook's 1773 exploration vessel, the first ship to cross the Antarctic circle.

In May 2007, the University of Cincinnati's Center for Surgical Innovation and the 12th NEEMO mission invited five teams of elementary and junior high students to a hands-on robotic demonstration competition. Each team moved rings from one peg to another in four different robotic surgery challenges: using laparoscopic graspers, using the graspers with one eye closed, manipulating hand-controlled robotic arms, and using the da Vinci robotic surgical system. The winning team was awarded the opportunity to control the surgical robot Raven at a community educational program at the Cincinnati Museum Center.

Other Live Interaction

In 2009 and 2010, the PLRP hosted three special visitors: elementary and high school teachers from schools in the Greater Vancouver Area. These teachers lived at Pavilion Lake for a few days, to study what the researchers were doing and to practice exploration operations. By the end of their stay, they had new science lessons to share with their students, like classifying microbialites and using an inclinometer to measure slopes. Having this personal experience—conducting real exploration studies in a unique analog setting—will be an invaluable tool in communicating the importance of science research to a new generation of potential explorers.

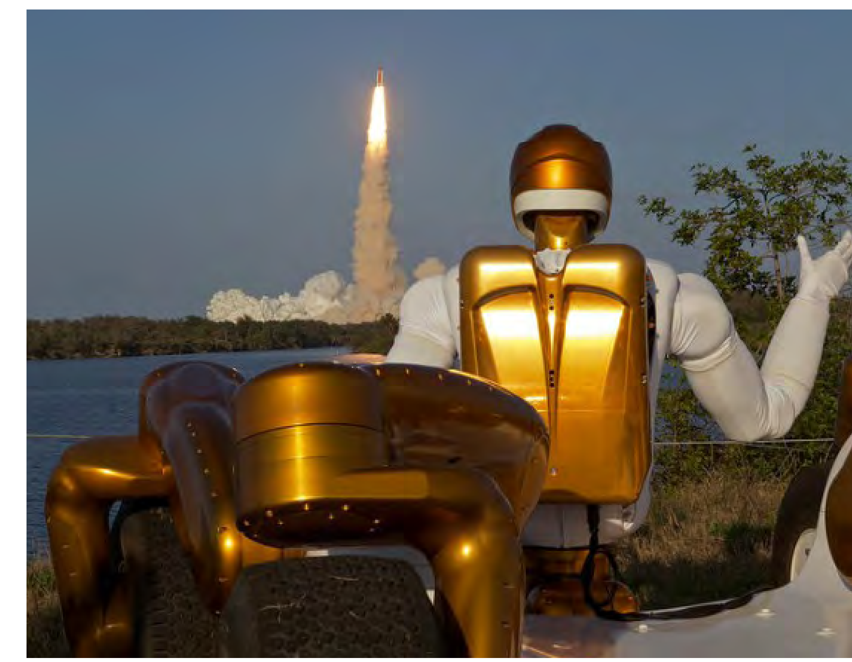
In a special DLN webcast event in May 2010, teachers and students from the Middle School Aerospace Scholars program were given the opportunity to conduct their own research on a NEEMO mission. While someone navigated a rover on the ocean floor, students recorded the time and distance the rover traveled, noting landmarks along the rover's route, such as coral and rocks. Afterward, the students used their measurements to create a map of the ocean floor, including the locations of noted landmarks. The experience gave the students an opportunity to learn the challenges and possibilities of learning about a foreign body through robotic exploration.

Conclusion & Next Steps

As NASA continues building a pathway to future human exploration of planetary bodies such as the Moon, Mars, and near-Earth asteroids (NEAs), the need for detailed operational planning and for refining exploration technologies will increase. Analog missions performed in extreme environments on Earth continue to help NASA answer challenging exploration questions. Detailed planning is already underway for analog missions to Desert RATS, NEEMO, HMP, and Pavilion Lake in 2011. Each of these analog studies, as well as the ISRU analog study in Mauna Kea, is planning for 2012 missions. NASA plans to expand the scope of analog missions by testing the telerobotic operations of the astronaut-assistant robot, Robonaut 2, which was launched to the International Space Station (ISS) in early 2011. While on the ISS, Robonaut 2 will test procedures for future NEA missions, representing the first beyond-Earth analog mission.

The successes from previous analog missions have already helped improve technologies designed for space exploration, refine operational plans for conducting scientific research, optimize communications and exploration approaches for long-duration roving missions, and test configurations of confined living spaces. A multitude of specific questions about exploration operations and technologies have been answered on previous analog missions, such as determining the best angle for a habitat ladder in a reduced-gravity environment or the number of explorers required to assemble an inflatable habitat. Future analog missions will continue to help ensure successful technology development, realistic requirements development, and integrated mission operations, to reduce the risk and cost for the future of human exploration of space.

Analog missions will help NASA prepare for a range of human exploration activities, here an artist concept of an astronaut anchoring to the surface of an asteroid.



Robonaut 2A looks on as Robonaut 2B is launched aboard the Space Shuttle to start a new era of analog mission testing, by testing operations for a future NEA operation on the ISS.

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Chapter Endnotes

DRATS Endnotes:

1. Joe Kosmo and Barbara Romig, "Desert RATS: Research and Technology Studies," presentation.
2. Joe Kosmo and Barbara Romig, "Desert RATS: Research and Technology Studies," presentation.
3. Dean Eppler and Doug Ming, "Science Operations Development for Field Analogs: Lessons Learned from the 2010 Desert Research and Technology Test," *42nd Lunar and Planetary Science Conference 2011.*
4. Jacob Bleacher, "Desert RATS: Space Exploration Vehicle Versus Lunar Rover," *Desert RATS Analog Blog,* posted September 13, 2010, accessed April 7, 2011, http://wiki.nasa.gov:80/cm/blog/analogsfieldtesting/posts/post_1284413644655.html.
5. Robert Howard and Chip Litaker, "Desert RATS: Human Factors," *Desert RATS Analog Blog,* posted September 8, 2010, accessed April 7, 2011, http://blogs.nasa.gov/cm/blog/analogsfieldtesting/posts/post_1283965133375.html.

NEEMO Endnotes:

1. "Aquarius Overview," *Aquarius Reef Base,* accessed April 25, 2011, http://aquarius.uncw.edu/about/overview.
2. "Aquarius Reef Base Location," *Aquarius Reef Base,* accessed April 25, 2011, http://aquarius.uncw.edu/about/about_location.
3. M.S. Bell, P.J. Baskin, and W. L Todd, "NEEMO – NASA's Extreme Environment Mission Operations: On to a NEO!" *42nd Lunar and Planetary Science Conference,* 2011, accessed April 25, 2011, www.lpi.usra.edu/meetings/lpsc2011/pdf/2162.pdf.
4. "Aquarius User Manual," *Aquarius Reef Base*, accessed April 25, 2011, http://aquarius.uncw.edu/about/usermanual.
5. "NEEMO," *National Space Biomedical Research Institute,* accessed April 25, 2011, http://www.nsbri.org/SCIENCE-and-TECHNOLOGY/Neurobehavioral-and-Psychosocial-Factors/NEEMO/.

   SRI International, "SRI International Joins NASA's NEEMO 12 Undersea Mission to Demonstrate Image-Guided Remote Surgery," *[SRI Press Release]* May 3, 2007, accessed April 25, 2011 http://www.sri.com/news/releases/050307.html.

HMP Endnotes:

1. Matthew C. Deans, "Field Testing Robotic Follow-Up for Exploration Field Work," presented at *42nd Lunar and Planetary Science Conference,* (The Woodlands, TX: March 7, 2011).
2. A. C. Schuerger and P. Lee, "Extremely Low Levels of Dispersal Observed for Human-Associated Microbes into a Local Pristine Terrain during a Simulated Moon Traverse on Sea Ice along the Northwest Passage in the Arctic," presented at *Astrobiology Science Conference 2010* (2010); Pascal Lee (NASA Ames), interview by author, March 17, 2011.
3. Pascal Lee, Stephen Braham, Terry Fong, Mark A. Helper, Jose Miguel Hurtado Jr., Chris McKay, and John W. Schutt, "Planetary Field Geology: Right and Wrong Lessons From Terrestrial Analogs," presented at *2010 GSA Denver Annual Meeting,* (Denver, CO: October 31, 2010); Pascal Lee (NASA Ames), interview by author, March 17, 2011.
4. "SpaceRef Sponsored Research," *SpaceRef.com,* accessed March 29, 2011, http://research.spaceref.com/; "Haughton-Mars Project: July 2010 Archives," *Haughton-Mars Project,* accessed March 29, 2011, http://www.marsonearth.org/2010/07/; and Andrew Vowles, "My Favourite Martian Digs," At Guelph, 51:1 (2007), accessed March 29, 2011, http://www.uoguelph.ca/atguelph/07-01-17/profile.shtml.

PLRP Endnotes:

1. Henry Bortman, "Discoveries in the Deep: How Astronauts Practice to Explore Other Worlds," *Space.com,* November 12, 2009, accessed March 30, 2011, http://www.space.com/7517-discoveries-deep-astronauts-practice-explore-worlds.html.
2. Darlene Lim, G. L. Warman, M. L. Gernhardt, C. P. McKay, T. Fong, M. M. Marinova,…D. Williams, "Scientific field training for human planetary exploration," March 2, 2010, accessed May 9, 2011, http://ucalgary.academia.edu/BenCowie/Papers/316386/Scientific_field_training_for_human_planetary_exploration.
3. A. C. Trembanis, J. Gutsche, and S. H. Nebel, "Precursor Exploration Missions in Kelly Lake, British Columbia-MARSLIFE project," December 2010, accessed May 9, 2011, http://adsabs.harvard.edu/abs/2010AGUFM.P13B1399T.
4. "About Nuytco – Phil Nuytten," *Nuytco Research,* accessed May 9, 2011, http://www.nuytco.com/about/phil.shtml.com/; "Haughton-Mars Project: July 2010 Archives," *Haughton-Mars Project,* accessed March 29, 2011, http://www.marsonearth.org/2010/07/; and Andrew Vowles, "My Favourite Martian Digs," At Guelph, 51:1 (2007), accessed March 29, 2011, http://www.uoguelph.ca/atguelph/07-01-17/profile.shtml.

ISRU Endnotes:

1. "In-Situ Resource Utilization Analog Summary" http://www.nasa.gov/centers/kennedy/moonandmars/hawaii_testing.html
2. Kinoshita, Laura, "Turning Lunar Dust Into Gold," *Astrobiology Magazine,* January 8, 2009, accessed April 4, 2011 from http://www.astrobio.net/exclusive/2996/turning-lunar-dust-into-gold
3. Sanders, Gerald, "3rd International Hawaii Analog Field Test," presented at Directorate Integration Office Strategic Analysis Status Review, March 2011
4. Sanders, Gerald, "3rd International Hawaii Analog Field Test," presented at Directorate Integration Office Strategic Analysis Status Review, March 2011

   http://www.nasa.gov/exploration/analogs/hawaii_analog_2008.html

   http://www.nasa.gov/centers/kennedy/moonandmars/hawaii_testing.html
5. "International Lunar Surface Operations (ILSO) and In-Situ Resource Utilization (ISRU) Field Test," Field Test Result Presentation, April 6, 2010

Antarctic Habitats Endnotes:

1. *National Science Foundation Office of Polar Programs,* accessed March 30, 2011, http://www.nsf.gov/od/opp/support/mcmurdo.jsp
2. *United States Antarctic Program, McMurdo Station Webcam*, accessed march 30, 2011, http://www.usap.gov/videoClipsAndMaps/mcmwebcam.cfm
3. ILC Dover, "ILC Dover's Inflatable Habitat Survives 250 Days in the Antarctic," news release, September 11, 2008, accessed March 30, 2011, http://www.prlog.org/10116528-ilc-dovers-inflatable-habitat-survives-250-days-in-the-antarctic.html.
4. *Challenger Center: Name the Hab Challenge,* accessed March 30, 2011, http://www.challenger.org/hab/

Public Engagement and Education Endnotes:

1. *Jules Verne Films & Expeditions,* (accessed May 5, 2011), http://www.julesverne.org/en/Nos-films/passage-to-mars.html.
2. "faq," *GigaPan*, (accessed May 5, 2011), http://gigapan.org/faq/; *GigaPan,* (accessed May 5, 2011), http://gigapan.org/gigapans/66626/; and "What is a GigaPixel," *GigaPixel 360,* (accessed May 5, 2011), http://www.gigapixel360.com/what-is-gigapixel/.
3. *GigaPan,* (accessed May 5, 2011), http://www.gigapan.org/.
4. Henry Bortman, "What Do You Call a Microbialite?," Astrobiology Magazine, July 5, 2010, (accessed May 5, 2011), http://www.astrobio.net/index.php?option=com_expedition&task=detail&id=3545.
5. "Living on Mars…on Earth," *Challenger Center,* (accessed May 5, 2011), http://www.challenger.org/programs/marswebcast.cfm.
6. Rob Rogers, "Mars expert visits Drake High en route to Arctic," *Marin Independent Journal,* March 11, 2009, (accessed May 5, 2011), http://www.marinij.com/ci_11889730.
7. "Name the Hab Challenge," *Challenger Center,* (accessed May 5, 2011), http://www.challenger.org/hab/.
8. University of Cincinnati, "NASA Extreme Environment Mission Teaches Local Students About Space, Robotics—and Other 'Cool' Science," news release, May 8, 2007, accessed March 30, 2011, http://healthnews.uc.edu/news/?/4874/.