# Going to Extremes
# NEEMO Case Study

In human space flight, crew preparation is paramount. NASA employs various tools in order to best prepare its crews; simulation and simulators, training for specific extravehicular activity (EVA) tasks in its Neutral Buoyancy Laboratory, and survival training. Apollo astronauts participated in desert wilderness survival to hone their skills. NASA has a long history of using terrestrial based activities as space flight analogs to advance science, test hardware and techniques, and develop crew leadership skills and team solidarity.

The NASA Extreme Environment Mission Operations (NEEMO) is a unique analog that merges elements to develop leadership abilities and build team cohesion with the execution of genuine mission objectives required for human space flight missions, all in an extreme environment. During NEEMO missions, astronauts become aquanauts and simulate living on a spacecraft, testing EVA techniques and tools for future space missions. Crews build leadership skills in an extreme setting, executing relevant mission objectives, allowing the astronaut-aquanaut to develop a genuine mission rhythm. What lessons can be learned from this extreme analog, and how are they being applied to current and future exploration objectives?

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**Aquanaut**

A diver who remains at depth underwater for longer than 24 hours.

### A Connection between Space and the Sea

One of NASA's Mercury 7, America's first class of astronauts became the connector between space and the sea. In the year following his 1962 mission, U.S. Astronaut Scott Carpenter met Jacques Cousteau. After learning of Carpenter's interest in undersea research, Cousteau recommended that he consider the U.S. Navy's SEALAB project. Carpenter obtained permission from NASA to take a leave of absence to participate in the project, and in July 1964, he joined the SEALAB team.[1]

SEALAB I, II, and III were experimental underwater habitats developed by the United States Navy in the 1960s to prove the viability of saturation diving and humans living in isolation for extended periods of time. The knowledge gained from the SEALAB expeditions helped advance the science of deep sea diving and rescue, and contributed to the understanding of the psychological and physiological strains humans can endure.[2]

In 1965, for SEALAB II, Carpenter spent 28 days living on the ocean floor off the coast of California. SEALAB II coincided with Astronaut Gordon Cooper's Gemini 5 mission, and he and Aquanaut Carpenter held the first conversation between a craft in outer space and one on the ocean floor.

After suffering several injuries Carpenter was deemed ineligible for spaceflight and further deep-sea missions. He returned to NASA as Executive Assistant to the Director of the Manned Spacecraft Center (Now Johnson Space Center [JSC]), then joined the Navy's Deep Submergence Systems Project, as a Director of Aquanaut Operations for SEALAB III in 1967.[3]

Carpenter spent the last part of his NASA career developing underwater training to help astronauts with future spacewalks.

### Birth of an Undersea Analog

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Growing up in the shadow of Kennedy Space Center and then the Manned Spacecraft Center, with a father deeply engaged in human space flight, Bill Todd was sure to be influenced by space exploration. Todd was also inspired by his father's best friend from childhood and Astronaut Carpenter, for not only his space exploration achievements, but more so for his interest and efforts in undersea exploration. Carpenter, considered a family member, shared with stories from Todd about his experiences with SEALAB project as an aquanaut.

Todd spent his formative years diving in the Florida Keys. Surrounded by early pioneers of human space flight, astronauts, engineers, technicians and controllers, he watched the achievements of Apollo Program. Todd followed Carpenter's career at NASA, listened to his SEALAB experiences and other exploits with great interest. Sunday evenings in the Todd household were dedicated to watching the Undersea World of Jacques Cousteau.

It was not a surprise that Todd found a career in space exploration at JSC. As a Simulation Supervisor in Spaceflight Training of the Flight Operations Directorate (including the Neutral Buoyancy Laboratory [NBL]), Todd was responsible for developing and executing multi-national simulations used for training astronauts and flight control teams. He has also worked as an Operations Lead at the Mission Control Center in Moscow, Russia. Todd spent a majority of his time in the Shuttle Mission Simulator, training astronauts how to fly the vehicle, operate systems, and dealing with contingencies. As a pilot, Todd enjoyed the work. However, it became evident that missing from the training was the component of crew dynamics.

> *"AT AN EARLY AGE I FORMUALTED THE IDEA THAT SEA AND SPACE WERE VERY SIMILAR; I RECOGNIZED THE SYNERGIES BETWEEN THE EXTREME ENVIRONMENTS"*
> *BILL TODD, Project Manager for Exploration Analogs*

One of the most important aspects of space flight is a crew's ability to function cohesively as a team to accomplish a goal, which is true in any extreme environment, whether military, or space exploration. Crews needed to be a cohesive, well-trained team aware of each other's strengths and weaknesses. There were limited opportunities for Shuttle crews to do this.

In his free time, Todd continued to pursue his undersea interest. Carpenter introduced him to undersea pioneer, Ian Koblick, who acquainted Todd with undersea habitation. Todd spent 30 days living in Koblick's undersea habitat, absorbing as much knowledge as possible. Todd continued to dive and learned how to pilot submersibles.

Todd integrated himself into the small community of manned undersea exploration. He met people, gain experience and earned credibility within the community. He began to formulate a plan to harness the synergies between sea and space. He was building the foundation to do just that.

During this time, Todd became aware of the Aquarius undersea habitat in the Florida Keys, just 10 miles away from another habitat he had been spending time in. He developed a vision that NASA and the Shuttle crews could benefit from experiences in an undersea habitat, and formulated a proposal to bring before management.

**Why an Undersea Habitat?**

An undersea habitat is isolated and extreme, just as the space environment. There are real consequences to actions. Injury and death are possibilities if training, rules and procedures aren't followed. Conditions can change rapidly, challenging the crew. One reason for the danger is the undersea environment requires participants undergo saturation diving. The difference between SCUBA diving and being in an undersea habitat is the element of saturation diving.

Saturation is the point at which the human body has absorbed all of the nitrogen that it can at a given depth. Divers cannot come to the surface without going through decompression because the body has to eliminate the excess nitrogen to avoid experiencing decompression sickness. An undersea habitat like Aquarius requires approximately 15 hours of decompression and prebreathe - breathing oxygen (similar to astronauts prior to embarking on EVA), then slowly bringing the habitat back up to surface pressure before crew can surface.

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Todd envisioned undersea missions in which crew members could perform “sea walks”, similar to EVAs. Crew members could be weighed out to zero or 1/6th gravity to mimic planetary gravity. It had to be a real mission, not a simulation. With his experience in astronaut training, Todd understood what would be required; the effort had to be high fidelity enough to offer astronauts a genuine and valuable training experience.

> *“PHYSIOLOGICALLY, YOU CAN FEEL CHANGES, GOING FROM TWO AND A HALF ATMOSPHERES BACK UP TO ONE ATMOSPHERE AND THEN BACK DOWN AGAIN, BEFORE YOU C OME OUT OF THE HABITAT. IT'S A REAL EXTRE ME ENVIRONMENT. IT'S NOT A SIMULATOR, IT'S NOT PRETEND.”*
> *BILL TODD*

Todd developed a proposal and approached Flight Operations Directorate management. While they saw benefit in the proposal, he had to gain JSC senior management approval for the effort. Randy Stone, JSC Deputy Director politely listened to the presentation. Todd had conducted massive research and gained significant experience, which provided credibility. Stone found the proposal interesting, Todd enthusiastic, and offered his support.

Enlisting Marc Reagan, a Space Station Training lead, and Astronaut and former professional and commercial diver Michael Gernhardt and Astronaut Dafydd "Dave" Rhys Williams, M.D., of the Canadian Space Agency, Director of JSC’s Space and Life Sciences Directorate, a foundation was created to make NEEMO a credible training analog.

Todd met with the National Oceanic and Atmospheric Administration (NOAA) and the University of North Carolina Wilmington who ran the Aquarius undersea habitat, through NOAA. Astronaut Kathryn Sullivan, who Todd trained for her Hubble Space Telescope repair mission, had departed NASA and was chief scientist at NOAA offered her support. The Director of NOAA agreed to the collaboration. Todd was invited to participate in a marine science mission, Sea Test and in 2000 became the first NASA aquanaut.

Upon his return, Stone gave Todd approval to move forward. NEEMO was now a reality.

**Developing a NEEMO Mission**

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Todd gathered his team and set about developing objectives for the first NEEMO mission. Traceable objectives, relevant to NASA's mission are required to make NEEMO successful. Those objectives must also reflect what can and cannot be done in the undersea environment. The team's expertise in crew training mandated NEEMO objectives be relevant to NASA's goals.

NEEMO has both interior and exterior objectives. For interior objectives, the team worked with the Space and Life Sciences Directorate to set human behavior performance goals. Experts were brought in to look at habitability and space, colors and lighting environmental, and human factors. Physicians provided input on what pieces of equipment can be used in a saturated environment (2.5 atmospheres).

The NEEMO team went into the water column, testing communication and mission control concepts. The group studied how far they could translate from the habitat and perform relevant tasks such would done on the moon; talking to mission control while walking on the lunar surface, examining rocks and determining which are high graded to bring back to Earth. NEEMO missions, and crew objectives are informed by NASA's exploration plan, whether planning to visit the lunar surface, an asteroid or the ISS. The NEEMO mission plan, timeline and objectives adapt to NASA's current needs.

Media outreach and educational events are incorporated, and the mission timeline is populated to best simulate a space mission, even including crew doctor visits, as is done on the International Space Station (ISS).

Todd commanded the first mission - a one-week stay inside Aquarius. He was joined by Astronauts Gernhardt, Williams and Mike Lopez-Alegria. NOAA offered mission objectives; coral and undersea limestone were used as an analog for lunar rocks. NEEMO crews would do photography and videography, and lay transects to measure coral health. This offered two beneficial returns, one being to marine scientists, contributing to NOAA's database on coral health and mortality rates in the Florida Keys, and the other to the NEEMO crew learning and training to do tasks that are analogous to those required to work on the lunar surface.

NEEMO has various leads in numerous areas. Physicians, geologists, and planetary scientists are responsible for bringing the content for the study. Other leads come from the EVA Project Office, responsible for the types of activities will be performed on the mission, its duration, what tools are needed, and for developing those tools. Individuals from the Engineering Directorate are brought in to work with EVA tools personnel develop those tools. Representatives from Safety and Mission Assurance, the Astronaut Office, and External Relations are also on the NEEMO Team. Each, whether scientist or engineer are all certified have been recognized as an expert in their field in order to be accepted as members of the NEEMO Team. Each must exhibit personal responsibility and initiative, and the characteristics of flexibility, creative problem solving, and calm when encountering contingencies. Individuals routinely seek the opportunity to join the NEEMO team to enhance their robust expertise.

Further, each member is assessed for their relevancy and what their contribution is to the team. If a NEEMO mission's focus is telemedicine, the physician must be capable of not only diving, and working as a member of the team, be well versed in teleoperations and tele-robotics and be conducting research directly applicable to NASA's objectives. Each team member must be physically fit and mentally prepared to undertake the month-long missions.

After learning of the specific NEEMO mission and objectives, the JSC Astronaut Office provides the names of the crew to participate in the mission. The European Space Agency (ESA), CSA and Japanese Aerospace Exploration Agency (JAXA) have realized the value of the program provide crew member. Numerous ESA, CSA and JAXA astronauts have participated in missions. A swim test is required for all NEEMO mission crew.

Missions are run out of JSC's Exploration Analogs Office. A call is sent out for proposals for the upcoming mission. Principal investigators and researchers with a nutrition study or physiological research on bone density study are eager to join the missions. Researchers and investigators see value in the extreme environment, the seriousness of the effort and that the proxy scientists, end operators are astronauts. Some contact the NEEMO office; they have either worked with NEEMO previously or learned about the activity from other NASA Centers. The U.S. military branches, especially the Navy have utilized NEEMO for research. Numerous universities have worked with NEEMO and hundreds of experiments performed.

Each mission has different objectives, needs, tools, and hardware and requires the choreographed effort of myriad organizations, including their own Mission Control Center (MCC) and dedicated CapCom. What may be considered the MCC Back Room on land, are the individuals prepping for the needed daily mission tasks and equipment, reviewing procedures, and troubleshooting any issues. Hardware may require being set on the seafloor prior to the morning's mission activities. Detailed crew procedures are developed for each NEEMO mission in a similar format as those on ISS.

A support vessel and dive teams may be necessary. Constant communication is required between the vessel, the back room, MCC, and the dive team so that all of the hardware is splashed at the appropriate time. Dive support teams in the water assist with umbilical management and other tasks depending on the specific mission objectives. The support team also ensures hardware fit. Spares may require, and equipment and tools swapped. This adds layers of complexity to each mission in addition to managing the crew in the water column.

**Remaining Relevant**

Every NEEMO mission is a proving ground for technology and processes needed in space exploration. Tools can be developed and assessed on NEEMO for later use on the ISS. 3D printing was utilized on NEEMO prior to being sent to the ISS. While 3D printers were not placed in the habitat, one specific NEEMO mission offered a shore-side 3D printer for the crew's disposal. The crew was encouraged to provide ideas that would aid in achieving their objectives. Underwater tags were printed for pre sampling surveys. Crew members had to nail the tags into coral. The nails were provided in Ziploc bags and accessing the nails while wearing work gloves proved to be next to impossible for the NEEMO crew. A 3D printed nail holder was conceived and created by the support team and modeled that evening, printed that night and sent on the support boat the following afternoon. The endeavor simulated what might be needed in a lunar or Martian expedition, further illustrating the creative problem solving and flexibility needed for exploration.

> *"IT'S A REAL MISSION DOING REAL, STRATEGIC SCIENCE AND OPERATIONS THAT APPLY DIRECTLY TO HOW WE WILL OPERATE, FEEDING RIGHT INTO THE SCIENCE THAT WE SPACE STATION. IT'S NOT INDEPENDENT OF IT. NEEMO WAS ABSOLUTELY THE BEST OVERALL ANALOG TO WHAT IT WAS LIKE TO LIVE IN THE SPACE STATION."*
>
> *NICOLE STOTT, U.S. Astronaut and NEEMO-9 Aquanaut*

NEEMO missions have replicated and evaluated scenarios for using science instruments and tools on the lunar surface; obtaining geological core samples, using augmented reality guides, studying body composition, sleep, physiology, and psychology, providing scientific and engineering feedback on a new spacesuit design to work and walk on the moon, tele-robotic surgery, with physicians providing remote guidance, and sequencing DNA that later transitioned to the ISS.

NEEMO also works to advance technologies involved in procedures documentation, crew scheduling and more. NEEMO has examined independent self-scheduling, and automation to give the crew flexibility so that they will have more free time, something that can be transferred to the ISS.

**NEEMO Safety**

Every aspect of NEEMO is assessed for risk, and that risk either mitigated or accepted. Todd has performed an Operation Readiness Review (ORR) for the entire project. The JSC Center Director, senior leadership and representatives from each Directorate attended the presentation. All aspects of NEEMO from operations through safety were reviewed. The entire NBL complex is certified by the very same process. Safety is the foundation of the NEEMO project. Todd is proud of the safety hazard review he performs for every single activity on every single mission. He must provide a response to every action assigned, and answer every question.

Safety assessments are performed at two levels. At the ORR level are those things are consistent every mission: going to 2.5 atmospheres to the habitat at two atmospheres, decompression, the potential of getting lost in the water column, electrical and environmental hazards, the possible failure of the life support system, and marine life encounters. A hazard assessment is performed and each risk categorized. It is baselined, and reviewed annually. Additionally, should a new tool be required for a specific NEEMO mission, a detailed hazard assessment is performed and an appendix added to the standard safety assessment.

NASA safety offers input on what will be undertaken each mission. Todd presents Training Readiness Review. NEEMO has developed a reputation for providing and executing rigorous TRRs and documenting safety.

Failures have occurred in the undersea environment that could have been catastrophic elsewhere, specifically with a commercial off the shelf drill that experienced a rapid disassembly. Its battery went into thermal runaway. Thankfully, it had not been provided to crew members. The support team was splashing down equipment to be used when the failure occurred. The same drill was in use at the NBL by support divers. A failure investigation was performed and an agency wide alert issued. While unfortunate, the incident alerted the NASA to the potential of a hazardous, catastrophic experience.

NEEMO team members reached out to the company manufacturing the drill, which then made improvements to the tool. NASA obtained all the necessary approvals, and is now using the improved tool with additional safety measures in place.

**Funding NEEMO**

NEEMO leadership connects with external partners to help offset the cost of each mission. Relevant science is requested, which in turn brings in resources. Initially, funding was provided from various organizations and programs across JSC and the Agency. NEEMO budget came from primarily from principal investigators, NASA Headquarters, and from NASA's Advanced Exploration System Division. Today, a significant level of NEEMO resources are contributed by entities external to JSC.

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Todd and Reagan share the NEEMO experience in numerous roadshows all over the world, working with organizations eager to be part of the missions. The two negotiate how the business or institution can contribute to the goal of the analog; efforts must be value added for both their organization and NASA.

Todd and Reagan have created a partnership model that works exceptionally well, built on providing results. NEEMO is presented an incubator, bringing in as much as possible, and delivering more than asked. Customers routinely return to NEEMO, finding it to be a good investment.

The COVID-19 pandemic has temporarily closed the Aquarius habitat.

**Lessons Learned**

- **An analog's relevancy requires constant examination of lessons learned. Each NEEMO mission captures a list of lessons specific to that mission.** Lessons are always captured about what makes a good analog for astronaut training. What was done on specific mission to make it a valuable analog? The myriad lessons learned are categorized. For example, one specific NEEMO mission may result 10 pages of lessons learned on the topic of communication. Good communication between mission control and the crew is vital, especially so when performing a spacewalk. During one NEEMO mission it was difficult to have good through-water communications unless both parties were on a hard line; communications weren't robust enough to provide good analog for space flight. The NEEMO team transitioned to wired communications with fiber running back to the Aquarius habitat to provide clearer communication and to make the analog relevant.
- **Be nimble and be adaptable**. NEEMO been in existence for 20 years due in some measure to being able to rapidly create a relevant mission plan, timeline and objectives - all adapted to NASA's needs at a specific point in time, whether the goal is to visit an asteroid, Mars or the lunar surface.
- **Operate in a businesslike way**, being judicious about resources, personnel, objectives, safety and training. Run the project like a business.

- **Treat every external customer as a highly valued client.** Listen to their needs, understand the value proposition NEEMO offers them. Seek to exceed their expectations.

> *"IT MAKES ME FEEL GOOD WHEN WE GO THROUGH THE SAFETY PROCESS, PEOPLE KNOW YOU'VE LOOKED AT EVERYTHING AND ARE WILLING TO LET YOU TAKE OUR PRECIOUS, HUMAN COMMODITIES AND DO THIS."*
> *BILL TODD*

- **Maintaining focus on safety is crucial**, to researchers, crew and support teams. Safety panels are not seen as arduous, but as extremely important and appreciated. The astronaut office is comfortable with how rigorous NEEMO is regarding safety, and how the team work to consider safety in every aspect of every mission.
- **Bringing in relevant science not only brings resources; it contributes the highly valued science needed for space exploration providing the astronauts actual science and mission objectives to perform.** *There is no busy work.* Astronauts are not asked to perform activities that are not relevant to what a principal investigator desires.
- **Astronauts have affirmed they find the experience valuable, stating time and again that NEEMO is the most relevant experience they participated in prior to space flight**. Their feedback further validates NEEMO's value. To date, there are 60 aquanauts who have also been to space.
- **Don't engage in activities that don't have a definitive objective and connect to NASA's gaps in exploration.**
- **For the analog to retain value and credibility, support team members should be recognized experts in their fields.**
- **Analogs remain an excellent proving ground for technology**. NEEMO offers an opportunity which can be used in tool development; to explore ideas and determine what should and should not be pursued. A piece of equipment can be developed, sent to NEEMO, tweaked or repaired if it fails. NEEMO has taught tool designers the value of taking the time to design considering a tool's environment and purpose.

## Current NASA Analogs

**Isolation and Confinement Analogs:**

- HERA - a three-story habitat analog for isolation, confinement, and remote conditions in exploration scenarios
- NEK/SIRIUS – at the Institute of Biomedical Problems at the Russian Academy of Sciences, Moscow, Russia, a multi-compartment closed habitat analog for isolation, confinement, and remote conditions
- Antarctic Stations - Closely equals the conditions & stresses likely on a long-duration human mission

**Bedrest Analog:**

- :envihab - Tests possible countermeasures for negative effects of microgravity

**Radiation Analog:**

- NASA Space Radiation Lab – NASA teamed with the U.S. Dept. of Energy to help assess health risks of cosmic radiation

**Other Analogs:**

- Human Exploration Spacecraft Testbed for Innovation & Advancement - a high-fidelity, human-in-the-loop, Lunar/Mars surface analog to support next generation human exploration missions.
- NEEMO
- Parabolic Flight - Simulated microgravity dedicated to scientific experiments and space equipment technological testing
- ACC - eight experimental chambers used to simulate long-duration space flight
- Concordia – in Antarctica, operated by the French Polar Institute and the Italian Antarctic Programme. Crew members winter-over as part of psychological, physiological, and medical research lasting the entire winter.
- Desert RATS - evaluates technology, robotic systems & EVA equipment for future missions in space, helping engineers better design, build & operate equipment, and establish requirements for operations & procedures.
- Pavilion Lake Research Project - Pavilion Lake, British Columbia, Canada, is a field site for Earth scientists & astrobiologists interested in research in the search for life in our solar system and beyond.
- Haughton Mars Project - Part of a research facility on the world's largest uninhabited island, Devon Island's harsh climate mimics environmental conditions on Mars and other planets, offering research opportunities. Arctic day and night cycle & restricted communications capabilities simulate the challenges of space flights. The Island is site of the Exploration program, aiming to develop new technologies, strategies, and operational protocols supporting exploration of the moon, Mars, and other planets.
- In-Situ Resource Utilization (ISRU) - Local natural resources at mission destinations, rock distribution and soil composition of Hawaii's volcanic deposits are an ideal terrain for testing ISRU hardware & operations.

- **NEEMO Teams develop and exhibit a better understanding of the risks inherent in the space environment.** Their experiences in the extreme underwater environment offer insight into the seriousness of space exploration and the risk to crew members.

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