

The *Aquarius* Underwater Laboratory: America's "Inner Space" Station

Dr. Steven L. Miller and Craig Cooper

**UNCW Center for Marine Science
National Undersea Research Center
515 Caribbean Drive
Key Largo, Florida 33037**

Introduction

As the International Space Station orbits earth in outer space, it may surprise you to learn that America also operates an "inner space" station called *Aquarius* (Figure 1), the world's only undersea laboratory dedicated to marine science and education. Owned by the National Oceanic and Atmospheric Administration (NOAA) and managed by the University of North Carolina at Wilmington (UNCW), *Aquarius* operates 4.5 kms offshore of Key Largo, Florida. The underwater laboratory is deployed next to deep coral reefs, 20 meters beneath the surface. As in its outer space counterpart, "aquanauts" explore and investigate an environment hostile to human habitation. *Aquarius* provides life support systems that allow scientists to live and work underwater, in reasonably comfortable living quarters, with sophisticated research capabilities.

Aquarius is a valuable national asset that advances our understanding of the ocean and its resources. The underwater laboratory also provides a unique window into our oceans, where special events and media access help to capture the attention and imagination of students and the public, worldwide.

A short history of living in the sea

In the brief history of undersea laboratories (also known as "habitats"), 65 separate programs operated during the last four decades (Koblick and Miller, 1995), including Jacques Cousteau's famous *Conshelf* project and American programs such as *Tektite*, *Hydrolab*, and the

US Navy's *Sealab* Program, managed by Dr. George F. Bond. The early days focused on human physiology; the Navy's Genesis Program (1957 - 1962) set standards that defined the birth of saturation diving and led to the *SeaLab* programs (Bond and Siteri 1993, Barth 2000). The technical achievements of the Genesis Program and *SeaLab* revolutionized the commercial dive industry. However, the science community was slow to adopt saturation diving techniques.

Most underwater habitats were best described as projects, rather than programs. Science objectives were not always well defined, operations and administration sometimes faltered, and funding was not sustained. Still, significant advances were made and the success of the *Aquarius* program is built on the legacy of these past efforts. The longest running program, in terms of missions conducted, was *Hydrolab*. Approximately 180 *Hydrolab* missions were conducted in the Bahamas (100 missions in the early to mid 1970s) and St. Croix, USVI (80 missions from 1977 to 1985). *Aquarius* is the second longest running program, and currently the only underwater laboratory dedicated to science operating in the world. Over 50 missions have already been completed using *Aquarius* (as of August 2000).

NOAA's and UNCW's *Aquarius* program

Aquarius was originally conceived and funded by NOAA's National Undersea Research Program (NURP) in the mid 1980s. The underwater laboratory was built by Victoria Machine Works in 1986-87. Initial deployment was in the U.S. Virgin Islands where 13 missions were conducted before Hurricane Hugo struck in 1989, and devastated St. Croix. *Aquarius* was retrieved from the seafloor in 1990 and was moved to North Carolina where it was refurbished under the direction of the University of North Carolina at Wilmington (UNCW). In 1993, the laboratory was redeployed in the Florida Keys National Marine Sanctuary, and supported 22 missions during the next three years. In 1996, *Aquarius* was recovered, refurbished and "re-invented" in partnership with UNCW, NOAA, and Harbor Branch Oceanographic Institution.

Many improvements were made to the system including construction of a semi-autonomous life support buoy that replaced a 17 by 34-meter life support barge. *Aquarius* was redeployed in 1997 (Figure 2) and operations resumed in 1998. Since then, *Aquarius* has supported over 20 missions and has a full mission schedule well into 2001. NOAA continues to be the primary source of funding for the program.

The Aquarius System

The fully equipped underwater laboratory includes several components. **The Aquarius “habitat” module** is an 82-ton double-lock pressure vessel that measures approximately 14-meters long by 3-meters in diameter. Scientists live and work inside the habitat when they are not on excursions, diving outside on the reefs. Entry is through the 20-m³ wet porch (Figure 3), which contains an open moon pool, dive equipment storage areas, and hot water heater and shower. There are two main compartments in the *Aquarius* module. The 14-m³ "entry lock," contains bench space for computers and experiments, power equipment, life support controls, small viewports and bathroom facilities. The largest living space is the 40-m³ "main lock." It includes berths for the six-person crew, computer work stations, two large viewports, kitchen facilities that include a microwave, instant hot water dispenser, refrigerator, sink, and dining and work areas (Figure 4). The main lock also contains life support controls, so both the entry and main locks can be independently pressurized.

The Aquarius baseplate is a 116-ton structure that provides a stable and level support base for the habitat. Each of the four legs contains 25 tons of lead ballast. The legs have seven feet of adjustment for leveling in variable seafloor terrain through the use of hydraulically-driven screw jacks. The habitat and baseplate were designed to survive severe storm conditions and have successfully weathered hurricanes in both the Caribbean and Florida.

The Life Support Buoy (LSB) is a 10-meter diameter buoy (Figure 5) that was provided by NOAA's National Data Buoy Center. The LSB is maintained above *Aquarius* on a five-point mooring using 2 and 5/8 inch diameter double-braided nylon lines connected to approximately 1.5-meter diameter spring buoys. Mooring plates were installed with anchor bolts grouted 1.2-meters into the seafloor. The LSB includes a communication tower and over 70-square meters of inside work space. Inside are two diesel-powered 40 kW generators, two 18.7 cfm air compressors, VHF radios, a cell phone, and a microwave broadcasting system. The LSB is linked to *Aquarius* by a three-inch diameter 42-meter unitized umbilical, which contains hoses that supply air from the compressors and oxygen from storage flasks, power lines from the generators, and 2 coaxial cables and 12 twisted pair wires for data and communications. The microwave telemetry system provides reliable audio, video, and data transmission between *Aquarius* and shore using "Wave Wireless Networking." Wave Wireless is a telecommunications and data communications manufacturer, and the specific system used is their SPEEDLAN 10ptp wireless link. The SPEEDLAN 10ptp is a 10-Mbps wireless point-to-point bridge that provides a secure wireless connection between *Aquarius*, the LSB, and shore. System upgrades are planned to increase bandwidth for improved video and voice communications that will support new broadcast and education programs.

A shore-based **Mission Control** center is located in Key Largo, approximately 12 kilometers from *Aquarius*, and includes a specially designed "watch desk" with computers and communication equipment linked to *Aquarius* via wireless telemetry. Also located on shore are: docks for the program's boats; office space; storage and work rooms for dive gear and equipment; an electronics shop; a six-person, dual-lock decompression chamber for emergency evacuation of *Aquarius*; two laboratories; and living accommodations for on-duty staff and visiting scientists.

The advantages of saturation diving for scientists

Aquarius scientists escape the limitations of conventional surface-based scuba diving through the use of a special technique called saturation diving. The most serious threat divers face when working underwater is related to "decompression sickness," also known as "the bends." Decompression sickness is caused by bubbles that form in the blood and tissues when divers stay down too long at a given depth, then ascend to the surface too fast. The bubbles get caught in joints and vessels, causing many symptoms that can include pain, paralysis, and ultimately even death. Instead of coming to the surface after diving, scientists who use *Aquarius* return directly to the undersea laboratory. As long as the Aquanauts don't go back to the surface they can use special dive tables to greatly increase their bottom time - to nearly ten times over what they typically have using conventional surface-based diving techniques. Without *Aquarius*, researchers are forced to make multiple dives of short duration from the surface, which also leaves them vulnerable to the complications of daily boat trips, unpredictable weather, difficulties setting up seafloor experiments that require power and computers from the surface, and frequent deep dives that increase the likelihood of getting the bends. At the end of each mission, aquanauts go through a 17-hour "decompression," where the pressure inside *Aquarius* is slowly reduced from ambient (the pressure at the working depth of *Aquarius* is 2.5 times surface pressure, or nearly 44 pounds per square inch) back to surface pressure (14.7 pounds per square inch). At the end of decompression the aquanauts "blow down" back to ambient depth in the entry lock, are met by ascent divers in the wet porch, and are escorted to the surface where they are picked up by boats and returned to shore.

Additional advantages provided by the *Aquarius* saturation system include the sophisticated power and communication capabilities of the habitat. Experiments can be set up on the reef similar to what might be accomplished back at a shore-based laboratory bench. A recent

mission powered high resolution infrared video cameras to record coral feeding biology, with recording decks inside *Aquarius*. *Aquarius* also provided power for the red lights to prevent unusual concentrations of plankton from developing. Further, plankton pumps were deployed at multiple depths in the water column, and divers out on the reef communicated with scientists back in the habitat to coordinate sampling and collecting schedules. Scientists also have email, telephone, and video conferencing capability to anywhere in the world. During another recent mission, a shore-based scientist had a complete mock-up of gear deployed from *Aquarius*, and was able to trouble shoot and solve equipment problems during the mission using data transmitted in real-time from *Aquarius*.

Scientists who study coral reefs need to work underwater. But bottom time is not the only limitation, cost is also important. The cost of running *Aquarius* compared to surface-based operations provides an interesting contrast. Conducting research on or under the ocean is expensive. Bottom time conversions from saturation missions to surface-based programs suggest that it would take at least 60 -70 days to match the same bottom time as a ten-day saturation mission. Sixty days in the field with a team of four divers can approach \$70,000 (\$900/day for a boat and dive support, \$120 day per diem for four people, and \$120/day hotel expenses for two rooms). Further, at the depths worked from *Aquarius*, surface-based diving is more rigorous than saturation diving. On a day-to-day basis, four divers could not possibly work more than 6 days without at least one day off, and over the course of several weeks additional time off is necessary. Larger dive teams could get around this problem, but costs would also increase. Repetitive deep diving schedules also expose divers to greater risk of decompression sickness than saturation diving.

So, how does *Aquarius* compare? One way to draw a comparison is to contrast the daily cost of *Aquarius* operations with the above surface-based cost estimates - assuming that the work

could even be conducted from the surface, which in many cases is not possible. Ten days in *Aquarius* costs \$100,000, or about \$30,000 more than a surface-based project. This is not insignificant. However, few academic scientists have 60 days available to spend in the field, so getting a lot of work done in a short amount of time is another beneficial aspect of the *Aquarius* program. Finally, *Aquarius* provides significant media access and public outreach capabilities that are not possible in conventional dive operations, and while the program's science mission is paramount these other activities are also valuable.

Aquarius science results

Aquarius is a national asset that supports scientists in their efforts to better understand our oceans and coastal resources. An open and competitive peer-review process is used to select proposals that are submitted to the program on an annual basis. Proposals target science and management issues of highest merit and relevance to NOAA, and in particular the Florida Keys National Marine Sanctuary. Over the course of almost 50 missions more than 200 scientists participated directly in the program, representing over 90 organizations including universities from across the U.S. and several foreign countries.

Aquarius scientists work to understand our changing ocean and the condition of coral reefs. Unfortunately, coral reefs are threatened worldwide by increasing amounts of pollution, overharvesting of fisheries, disease, and global climate change. Science achievements from *Aquarius* include discoveries related to the damaging effects of ultraviolet light on coral reefs, geological studies that use fossil reefs to better understand the significance of present-day changes in coral reefs, research that is rewriting the book on how corals feed, water quality studies that evaluate sources of pollution, and long-term studies of reefs to help distinguish between changes caused by natural system variability and humans (due to pollution and overharvesting). A few examples follow.

Coral Reef Assessment and Monitoring using saturation techniques

Aquarius provides the bottom time necessary to make detailed studies of deep coral reefs. A 1998 *Aquarius* mission evaluated the relative condition of corals at depths to 120 feet. The team found that hard coral colonies at the deeper depths were in better shape than corals in shallower (60 feet) water. This is significant because a substantial amount of deep-reef resource is found in the sanctuary, but little is known about its condition. Interestingly, high recruitment levels (the observance of new individuals) were noted at all study sites. This is a positive sign for reef condition and recovery - at least in deeper water. Soft corals and sponges dominated recruitment at the deeper sites, while hard corals dominated at the shallow site. Fish surveys resulted in abundance estimates for 111 species (132 fish species were documented). The benthic and fish data will be compared with baselines established in 1994 as part of a deep coral reef monitoring program in the Florida Keys National Marine Sanctuary. A mission conducted in August 2000 expanded the monitoring and assessment effort, including more detailed biodiversity studies on sponges, gorgonians, and gastropods. Since the *Aquarius* site is now a marine protected area (commercial and recreational fishing and collecting are not allowed) the fish surveys provide valuable information for managers about how "no-take" strategies are affecting reef dynamics.

Water quality and nutrient pollution

Extended bottom times and the ability to deploy sophisticated sampling devices on reefs during missions have helped scientists to understand factors that affect water quality on reefs in the Florida Keys National Marine Sanctuary. Water quality research conducted using the Center's shore-based research programs previously confirmed that sewage disposal practices used in the Keys contaminate nearshore waters (Paul et al. 1995). This information has helped

politicians and managers to balance the costs of modifying sewage disposal practices in the Keys (measured in the hundreds of millions of dollars) with the costs of possibly losing nearshore resources to polluted water. However, documenting offshore nutrient pollution, and tying pollution to reef decline has not been easy. Offshore of the Keys, using the *Aquarius* underwater laboratory, scientists documented changes in water quality caused by natural events - related to the reefs close proximity to the Gulf Stream and upwelling events - that deliver substantial amounts of nutrients, plankton, and particles to the reef (Leichter and Miller 1999, and the June 2000 mission). Understanding and quantifying this substantial natural system variability provides important perspective on the potential for sewage to be a significant offshore problem. *Aquarius* scientists have also searched for (by drilling monitoring wells at the *Aquarius* site to sample potentially contaminated groundwater that could be moving through the reef), and continue to seek, the "smoking gun" that could conclusively tie nutrient pollution to the demise of reefs in Florida. So far, evidence remains inconclusive. The research results illustrate the complexity that defines factors that affect how reefs look and function in Florida.

The mysteries of coral feeding biology - revealed

This project used video and other techniques to study the small-scale mechanisms that affect how corals feed and capture prey (Sebens et al. 1998, Heidelberg 1999). Usually, this work is conducted in the laboratory, but *Aquarius* provided computers, power, and the necessary bottom time to conduct this work directly on the reef (July 2000 mission). The advantage is that measurements are made under natural conditions, and the corals are not stressed by removing them from the reef for study. It is well known that water motion impacts coral biology, affecting processes such as coral growth, competition, larval dispersal, fragmentation, and sedimentation. However, even at short distances, the rate of flow over and around corals can change dramatically. Water motion also delivers prey to corals and enhances the uptake and exchange

of nutrients, oxygen, and carbon dioxide. The aquanaut team built and deployed sophisticated instruments to measure current speed and direction at the site, as well as flow over and around individual corals. Combined with high resolution infra-red video cameras, that were cabled from *Aquarius*, interactions among plankton and coral tentacles were documented that allowed the scientists to calculate coral feeding rates - the first measurements ever made under natural conditions.

Outreach from Undersea

The world class scientists who participate with the *Aquarius* program also contribute time and expertise to help explain what they do, and why it's important. The impact of their work has reached millions through scientific papers, media coverage, and outreach activities. Due to its visually appealing nature and novel approach to marine science, *Aquarius* receives significant media coverage including television (NBC, ABC, PBS, CNN, National Geographic, Discovery Channel, and Popular Science for Kids); radio (National Public Radio and Scuba Radio); and print (Scientific American, New Scientist, Geo Times, LA Times, and USA Today). *Aquarius* has twice teamed up with the internationally broadcast Jason Project. The most recent event, "Jason XI - Going to Extremes," was jointly produced with NASA in March 2000 and reached over 750,000 students with five live broadcasts daily for two weeks, and many more through the Internet.

Aquarius also fosters public awareness through its website at www.uncwil.edu/aquarius. Visitors can take a virtual tour of the undersea laboratory, view and download mission photos, learn about marine science, read expedition reports from the scientists, and watch real-time web cameras inside *Aquarius* and out on the coral reef.

Diving Into the Future

The evolution of *Hydrolab* and *Aquarius* from substantial shore support provided in St. Croix, to offshore operations in Florida, first using a mobile support barge and then the LSB, points toward even more autonomous operations in the future. For example, air storage banks located on the bottom, sufficient to support an entire mission, would eliminate the need for compressors now located in the LSB. Innovations in carbon dioxide scrubbing systems have already been tested in *Aquarius*. Modular construction of new habitat systems would allow for easier deployments and custom configurations based on individual site-based needs. And power systems located underwater, rather than from surface-based generators like the LSB, may soon be possible. Ultimately, only a communications buoy on the surface might give any hint of human habitation below. All of this points to increased system mobility, greater depth capability, and less surface support during missions, without sacrificing aquanaut safety.

The next generation of underwater laboratories will build on the successes of *Aquarius*, but challenges exist to provide even more cost-effective and flexible operations. A national debate is also underway regarding the use of remotely operated vehicles to replace human exploration and presence underwater. Arguments for machines to replace humans are based on considerations of cost and safety. However, programs like *Aquarius* and manned submersibles satisfy an essential element of the human spirit that cannot be met by robots. Further, human eyes still exceed the capabilities of cameras, and the creative potential of our brains to observe, explore, understand, and solve problems cannot be matched by computers. Human exploration in the extreme environments of the sea and outer space has captured the attention and imagination of our nation for almost half a century. As the International Space Station comes on line in outer space, it is time to refocus attention on our ocean planet and its "inner space station," *Aquarius*. The immediate future for *Aquarius* includes a full mission year planned for

2001, and refurbishment for 2002 and beyond is attracting national attention and support. *Aquarius* may be the only underwater laboratory operating in our oceans today, but based on its record of productivity and accomplishment, and the human spirit of exploration, it won't be the last.

References

- Barth, B. 2000. *Sea Dwellers: The humor, drama and tragedy of the U.S. Navy SeaLab programs*. Doyle Publishing Company, Inc. Houston, TX. 184 pages.
- Bond, G.F and H.A. Siteri (Editor). 1993. *Papa Topside: The Sealab Chronicles of Capt. George F. Bond, US Navy*. United States Naval Institute. Book News Incorporated. Portland, OR 270 pages.
- Heidelberg, K.B. 1999. *The effects of water flow and zooplankton prey behavior on scleractinian coral and heterotrophy*. University of Maryland (USA). 207 pp.
- Koblick, I.G. and J.W. Miller. 1995. *Living and Working in the Sea*. Flagstaff, AZ. Best Publishing Company. 438 pages.
- Leichter, J.J. and S.L. Miller. 1999. Predicting high frequency upwelling: Spatial and temporal patterns of temperature anomalies on a Florida coral reef. *Cont. Shelf Res.* 19:911-928.
- Paul, J.H., J.B. Rose, J.Brown, E.A. Shinn, S. Miller, and S.R. Farrah. 1995. Viral tracer studies indicate contamination of marine waters by sewage disposal practices in Key Largo, Florida. *Appl. Env. Microbiol.* 61(6): 2230-2234.
- Sebens, K.P., S. Grace, B. Helmuth, E. Maney, and J. Miles. 1998. Water flow and prey capture by three scleractinian corals, *Madracis mirabilis*, *Montastrea cavernosa*, and *Porites porites* in a field enclosure. *Mar. Biol.* 131(2): 347-360.