Inner to Outer Space

From where should NASA or the private industry select their next generation of astronauts? They need individuals with a thirst for adventure, meticulous attention to detail and unbridled enthusiasm for exploration.

The best choice for new astronauts lies in the ocean depths. Astronauts and aquanauts (NAUTS) are very similar, and a relationship between the two groups already exists. On a leave of absence from NASA, U.S. Navy astronaut Scott Carpenter worked the “Man in the Sea” project as a team leader in 1965, where he directed the team of divers. Many of the same traits are required for both space and undersea explorers to be successful.

From Night Stars to Sea Stars

The transfer of desirable habits from using aquanauts to fulfill the role of astronauts would greatly propel space exploration by reducing required training time. Additionally, some of the safety precautions and bailouts used in rebreather and expedition / exploration diving could be useful tools for space exploration.

Differences also exist between these two subcultures. Present-day astronauts ride in a large (2 thousand ton) rocket into space, orbiting the earth at 8 kilometers per second at altitudes between 180 and 650 kilometers. Aquanauts descend in a pressurized bell, as free-swimming divers or in a chamber, to depths of between 10 and 600 meters of sea water (msw) at a rate of between 3 and 40 meters per minute; they remain in that high-pressure environment until they decompress.

Even the differences have similarities though. When divers descend, the partial pressure of the gases they breathe (oxygen, helium or nitrogen) increases, according to Dalton’s Law. This law governs the delicate balance of breathing gases within a saturation dive chamber (SAT chamber). While the International Space Station (ISS) and present-day shuttle (orbiter) maintain normal oxygen content at normal sea level pressures most of the time, Dalton’s Law regulates the rocket boosters’ chamber pressure. The size of the fuelburning chamber is dictated by the requirement that the combustion must balance. Dalton’s Law governs the relation between the pressure and other variables. Both teams are regulated by many of the same laws although they are not manipulated in the same manner.

Both astronauts and aquanauts are generally small, tightly knit, highly trained and team-intensive groups of individuals. Both design, practice and memorize emergency procedures, and both require significant support in both personnel and equipment in their missions. Logistics training is a large component of every mission, and considerable planning and practice goes into both space flights and SAT dives.

NAUTS of both types must live in confined quarters for anywhere from five days to six months. Neither team has a general perception of day or night; and sunlight seldom penetrates the depths of a SAT dive. Even the minimal light that penetrates deep waters loses its red, orange and yellow tones, and without external light, everything appears green and blue. In contrast, the astronauts witness 32 sunrises and sets every day as they orbit the earth at greater than 4 miles per second.

Flexibility Is Key

NAUTS are the proverbial fish in the bowl, looking through portals and observing the expansiveness of the world as they move along. When in this tight environment, however, it’s essential to define clear roles of leadership as well as specific areas of responsibility. Still, everyone stands the prospect of acting as the engineer, ichthyologist, geologist, rigger as well as the janitor, launderer and cook. Personnel who can

multitask are quite valuable.

Because of the special environment of travel in space and underwater, a psychological profile must be generated for all NAUTS: compatible persons must be placed together so there is a maximum capacity for communication between team members. The physical stress of an altered environment, the alternating daylight patterns that create a potential for sleep deprivation, the taskintensive work schedule and the cramped living quarters make getting along an absolute necessity. You can't settle a conflict by walking around outside to clear your head when you're miles above or below sea level: all team members must put aside their personal aims and look to team-oriented goals.

Water is the best and most cost-effective environment in which to train an astronaut for the constant freefall of space (simulated weightlessness). To practice tasks, astronauts are made neutrally buoyant in their space suits and submerged in a neutral buoyancy laboratory. Before they attempt a maneuver or job in space, they simulate it underwater.

NASA astronauts are currently training for remote medical procedures in SAT chambers. The purely remote and compact nature of the SAT chamber imitates the conditions on the International Space Station or orbiter, where the medical technician has limited space. The astronauts have a finite amount of medical supplies both above the atmosphere and below the sea, so the training is characteristic of real conditions.

While in a SAT chamber, a physician who is simulated to be thousands of miles away on "earth" can talk through specific medical procedures with the unaffected astronauts. This training benefits both the saturation diving community and the astronauts and further demonstrates the similarities between the two communities.

For missions of extended duration, the astronauts are also being acclimated in these SAT chambers.
NASA Extreme Environment Mission Operations (NEEMO) is a program where the astronauts can get an in-depth start in learning about techniques and technologies that could serve space travelers when they fulfill the presidential decree and travel to the moon and beyond.

They dive in a SAT chamber off the coast of Key Largo, where they experience an environment in many ways as potentially hostile as that of space or other planets. In six such underwater missions, the astronauts have also tested equipment that may be flown in space. For the first time in a long time, human physiology research is being performed on these NEEMO dives. Astronaut crewmembers frequently remark on the similarity of working underwater and in space.

The NEEMO expeditions are not the first times NASA has sought knowledge from the sea. In 1969, two days prior to the Apollo 11 liftoff, NASA launched the PX-15 Ben Franklin, which carried a crew of six on a 30-day undersea voyage to study the Gulf Stream current and the prolonged effects on humans of living in a contained environment. NASA wanted to study the environment aboard the sub as an analog to life aboard a space station.

The data from this mission was to be incorporated into NASA exploration missions, but slipping timelines and the demand for precise work precluded the completion of this mission prior to the execution of Apollo 11's moon-shattering lunar landing. Because of the timing, the NAUTS' accomplishments from this mission were overshadowed by Americans looking toward the sky as another set of explorers sought to land on the moon. The information gathered from the crew of the Ben Franklin is still being used as a guideline to expeditions everywhere.

NAUTS share concerns with support and management personnel. In both scenarios the NAUT has very little

autonomy, acknowledging the need for support from the ground or topside, where a wider range of expertise may be available. Every moment of the day from work to sleep is arranged and coordinated by persons who are not actually on site. The delicate dynamics of dealing with an off-site manager take a significant time to master. Aquanauts have already become accustomed to off-site management and handle it well.

All NAUTS prefer to solve problems by themselves, however. Empowering them to problem-solve individually or as a team gives them valuable experience in manipulating their own environment and equipment and helps to build a more selfsufficient team.

A Comparison of Living Quarters

The atmosphere can be controlled, so no special suits are required within the confines of the ISS, orbiter or a SAT chamber. Metal walls keep the pressure inside the ISS or orbiter (in the vacuum of space) or outside the SAT chamber (in the more dense-than-air water). Because the atmospheres within the confines of the living quarters are selfcontained, they must be properly maintained to support life.

Mammals are unable to sustain life while breathing any medium other than gaseous combinations containing at least 16 percent oxygen. The atmosphere is maintained the same way in the ISS and orbiter as it is in a SAT chamber. In enclosed systems, the build-up of carbon dioxide (CO_2, the byproduct of oxygen metabolism) over a period of as little as 10 minutes could raise the level greater than human tolerances of approximately 6 percent by volume.

To solve this problem in orbiting vehicles, a simple series of fans cycle the breathing medium and forces it through “scrubbers,” which remove the CO_2. These scrubbers chemically bind the CO_2 and produce water vapor, moisture and chalk as a result. The water removed is sent to the water-andrecovery management subsystem. The scrubbers often contain a layer of charcoal to absorb and reduce odors.

Other systems add and homogenize oxygen so pockets do not occur; temperature and humidity control helps to circulate air, remove humidity and maintain the ISS and orbiter within a range similar to normal sea level pressure and oxygen content.

Heat control is crucial for the ISS and orbiter because of the significant changes in temperature in the vacuum of space. No atmosphere exists to hold the heat steady every 90 minutes as they pass from day to night and back again when orbiting.

Because of the complete isolation of space, recycling of water is extremely important. While normal SAT chambers do not include this level of intricacy or the need for collecting water, they perform CO_2 scrubbing, dehumidification, heating and odor removal in the same manner. Heating is extremely important in a SAT chamber because the surrounding water whisks heat away 25 times faster than air. Additionally, the metal walls of the chamber and the usually high helium content make the SAT divers feel uncomfortably cold.

SAT chambers are normally kept at a constant pressure (storage depth) regardless of how deep the divers need to work for their mission. If a SAT dive to a maximum depth of 120 msw – (more than 13 times the pressure at normal sea level) was required the storage depth would be ~90 msw. The atmosphere in the SAT chamber would be a threegas mixture (trimix) of helium, oxygen and nitrogen. The helium is used to offset the potential narcotic effects of nitrogen.

The partial pressure of oxygen (PPO_2) must be limited to 0.5 percent (the equivalent of breathing 50 percent oxygen in a normal surface pressure) so the divers do not experience symptoms of pulmonary

oxygen toxicity. Pulmonary oxygen toxicity is the “burning” of the alveoli due to prolonged exposure to higher concentrations of oxygen and manifests itself by irritation below the sternum, pain on inspiration, reduced vital capacity. Often these symptoms are preceded by a non-productive cough and “tickle” in the back of the throat.

The breathing media in the SAT chamber is not generally changed until the dive is finished and the divers are being decompressed. The pressure is consequently decreased during decompression until the divers are brought back to normal surface pressures.

During long duration stays in these “homes away from home,” hygiene is a significant factor. NAUTS produce waste products. For sanitation and comfort of the inhabitants, storage and removal of these are very important. In space, the excrement is sucked into a compartment and the liquid is removed and jettisoned and the balance of the matter is stored in a vacuum. The vacuum facilitates capture of the odor.

Some SAT chambers have hard-lined plumbing, which allows the occupants to use the facilities almost as easily as a normal restroom, although the system’s pipes must be reinforced to support the higher pressure. Most SAT chambers use portable receptacles, and liquid waste can be immediately jettisoned. The balance must be bagged and surfaced or stored. Because of the enclosed environment, the latter is generally discouraged.

Due to complete immersion of a SAT chamber and the nature of the work, removal of the moisture in the breathing media is difficult. This increased moisture, coupled with increased pressure and non-natural lighting sources, fosters an excellent breeding ground for bacteria. To lower the risk of ear infections, SAT divers need to apply an antifungal /antibacterial solution as a precaution. Since the heavy gear can chafe certain areas of the skin, NAUTS are also exposed to a higher risk of contact dermatitis. While astronauts do not experience the increased moisture and pressure levels, they must maintain the diligence to avoid open wounds and infections.

NAUTS are usually physically fit to combat the g-forces and decompression stresses. They generally maintain their physical prowess while on assignment. For astronauts, failure to exercise could weaken muscles to the point that they may not be able to stand or walk upon re-entry into earth’s gravity-rich environment. Moreover, if the heart muscle is not exercised, it could weaken. Additionally, the bones are biologically coded to absorb impact. Lack of impact causes the bones to become less dense by shedding calcium. If not exercised, bones could become more brittle and break when reintroduced to a gravity-rich environment.

As a consequence of exercise, NAUTS perspire. For aquanauts, this exercise adds to the already high moisture level, but it is not generally a problem. Astronauts do not have gravity to help remove the sweat. Moving air from a duct as well as use of towels aid in drying perspiration. If this moving air did not dry the astronaut, the sweat would stick to the skin and continually grow thicker.

Fresh water is at a premium for both sets of NAUTS. There is no shower on the orbiter or ISS. Astronauts use washcloths or sponges with a type of soap that wipes off with a towel. In a SAT chamber, NAUTS shower primarily in salt water, with a freshwater final rinse. They require special soap that will not break down in salt water. All gray water (not fresh) is jettisoned.

With nothing to force water downward, a shower in space facilitates free flying water. Given the amount of electronics on the ISS and orbiter, freeflying water could damage sensitive equipment. Due to the lack of ability to easily resupply storage tanks in space, a water recovery and management subsystem recovers and recycles water from the sinks, urine, the orbiters’ fuel cells and condensation from astronauts’ breath. A potable water processor refines gray water into drinkable water. Water quality is monitored closely by

another system. Fire is one of the greatest dangers in space or in underwater habitats, so measures are taken to mitigate the risk of combustion. The four elements of the fire tetrahedron needed for combustion are heat, fuel, oxygen and the chemical reaction. When one or more of those elements are exaggerated, the risk of combustion increases significantly.

Perhaps the most dangerous part of any space flight is the re-entry. Tile temperatures can reach 938 degrees C, and the leading edge of the wings can reach 1371degrees C. This increase in temperature can be problematic if given the correct fuel and enough oxygen.

Similarly, during the last portion of decompression, SAT divers experience a significant risk of combustion. To minimize decompression time, the PPO2 is raised to levels as high as 1.2 percent. This is the equivalent of a 120 percent oxygen environment. All other elements of the fire tetrahedron are subsequently decreased or negated to decrease the risk of fire.

Similarities When Leaving the Habitat

When a diver leaves the storage depth chamber, it is called an excursion. The decompression requirement for an excursion is predicated on the amount of inert gas in the breathing media. The only way to decrease the inert gas content is to increase the oxygen content in the breathing media. SAT divers use reclaimers or rebreathers to recirculate their breathing media instead of expelling it to the water.

These rebreathers capture the gas, scrub the CO2 from it and add oxygen just as the systems within the living quarters, albeit on a smaller scale. The divers need a higher concentration of oxygen in their breathing media while at work.

During extravehicular excursions for astronauts, they require minor changes in their suits. To combat the high molecular oxygen vacuum of low earth orbit (LEO) space, astronauts wear a full pressure suit called an extravehicular activity (EVA) suit. These suits supply oxygen for breathing and also maintain a pressure around the body to keep fluids in their liquid state. This suit is similar to high-tech rebreathers technical divers use.

A spacesuit has the added function of protection from small meteoroids and insulates the wearer from the extreme temperatures of space with an active cooling and heating system. Without an atmosphere to filter the sunlight, the side of the suit facing the sun may be heated to a temperature as high as 115 degrees C, while the other side, exposed to space, may get as cold as -155 degrees C.

The EVA suit pressure requirements are different from the sea-level pressure within the ISS or orbiter. If an EVA suit were filled with normal sealevel pressure while in a vacuum, the wearer could not move. (A diver who has ever overfilled a drysuit even slightly knows how hard it is to move.) The suit would be too rigid; the arms and feet could not bend and astronauts could not work. A low suit pressure (almost 1/3 of normal sea level pressure) is advantageous because it allows for flexibility and mobility of the suit during EVA. Because of Dalton’s Law, a lowering of pressure results in a reduction of the total amount of oxygen in the breathing space; therefore, an increase in the PPO2 is required to sustain life.

The increased risk of fire is an acceptable risk within the EVA suit because it has no electronic components. However, the ISS and orbiter have many electronic components and the risk of fire could be great if oxygen levels became higher than normal.

The saturation diver needs to be protected from the elements to which he or she would be exposed with a wet-, dry- or hot-water suit. Primarily, this protects the diver from the cold and the evaporative cooling of the surrounding sea water. In most areas of the world, sunlight does not penetrate to SAT dive depths;

therefore, the water at that depth can be as cold as -2 degrees C. Contrary to the vacuum of space, aquanauts can be exposed to water without an exposure suit, albeit only for a short duration. For divers, the main concern is a breathing medium.

The risk of separation from the living quarters is significant. Astronauts deal well with this problem because they normally use two connection points while on a space walk and move by pulling handover-hand or pushing.

Astronauts cannot move by paddling or swimming because there is nothing to push against in space. The risk of separation in a SAT chamber is real as well. Present-day SAT divers, untethered to the habitat, must take great care to not become disoriented.

One significant difference is the aquanauts are only exposed to weightlessness while their bodies are in the water, while the astronauts are weightless until they return to earth. If the astronauts are on a planetary mission, they may enjoy partial gravity.

Similarities in Physiology

While still within the ISS or orbiter prior to any space walk, the astronauts must prebreathe oxygen because of a large differential in pressure between the living quarters and EVA suit. Failure to perform a prebreathe (or adjust cabin pressures prior to space walks) could result in the transfer of dissolved nitrogen from the tissues to the astronauts' bloodstream. Because of the rapid decrease in pressure, nitrogen bubbles would form in the blood. After being attacked by phagocytes (cells that consume foreign bodies), they would be treated as foreign matter by their companion leucocytes (white blood cells).

In short, the astronaut could become "bent." The symptoms tend to occur either during or after an EVA and in severe cases could be fatal. The prebreathe procedure is similar to prebreathing using an oxygen rebreather. Prebreathing is done by inhaling from an isolated mask within the living quarters. These procedures are also performed in the EVA suits. This ensures that only the astronaut, and not the spacecraft, is exposed to a higher percentage of oxygen. During this process, the nitrogen absorbed in the tissues is reduced to the point that the risk of DCS is minimized. Changing the atmospheric pressure would decrease the time required for prebreathing.

While there are no reports of "space decompression sickness (DCS)," NASA sees a fairly high DCS incidence in ground trials in hypobaric chambers. However, they have very conservative acceptance criteria before they use a prebreathe protocol in space. A great deal of additional safety margin is incorporated prior to flight. Metabolic rates in the suit while prebreathing oxygen are slightly higher than a test subject at rest.

Why so? This is because the astronaut moves around and works against the pressurized suit. Research by Dr. Michael Gernhardt (NASA astronaut, Manager Of Environmental Physiology Laboratory and Principal Investigator Of Prebreathe Reduction Program, Johnson Space Center) at NASA has shown that even slightly elevated metabolic rates can enhance the nitrogen elimination and reduce the decompression stress. Consequently, astronauts use exercise during oxygen breathing to enhance nitrogen elimination. This plan works well but it has to be a very specific exercise prescription. Pairing high-intensity exercise with low-intensity exercise was the best for reducing nitrogen bubbles.

Similar concerns about DCS transpire when a saturation diver performs "excursions." Divers who increase depth (significantly) as a result of required activity below the storage depth may find the need to decompress back to the living quarters. Additionally, all divers need to decompress from every dive

regardless of depth. This decompression is normally in the form of a controlled ascent rate.

As divers proceed to the bottom of a deep saturation dive, they must be cognizant of signs of high-pressure nervous syndrome (HPNS). This is characterized in humans by dizziness, nausea, vomiting, postural and intention tremors, fatigue and somnolence, jerking, stomach cramps, decrements in intellectual and psychomotor performance, poor sleep with nightmares, and increased slow wave and decreased fast wave activity of the brain as measured by an electroencephalogram.

While the exact origin is unknown, HPNS is thought to be caused by high external pressures and exacerbated by the choice of breathing media and rate of descent. For instance, some divers experience a mild form of HPNS termed "helium willies" on rapid descents while breathing helium oxygen mixtures to depths as shallow as 92 msw. Beyond certain pressures (depths), the efficacy of a diver becomes extremely limited.

In contrast, when astronauts accelerate past 4 miles per second and begin the constant free-fall of orbit, many of them experience space adaptation syndrome (SAS), which is similar to motion sickness. Symptoms can vary from mild nausea, disorientation, vomiting to intense discomfort. Headaches and nausea are often reported in varying degrees. This ailment reportedly lasts two to four days. While pills for motion sickness could reduce the severity of the symptoms, the consequences of this medication could render an astronaut drowsy.

While astronauts do not generally suffer from SAT diver afflictions such as aseptic bone necrosis (bone death due to dissolved inert gas in the bone coming out of solution rapidly and destroying the bone), they experience bone loss due to living in micro-gravity conditions. Astronauts have limited stresses on their bones, but the lack of gravity causes the bones to decalcify. Special exercise machines are used to increase resistance. For cardiovascular activity and to diminish bone loss, astronauts strap themselves in and work out for 15 minutes daily on missions of seven to 14 day and 30 minutes a day on 30-day missions.

Technical and rebreather divers see symptoms commonly referred to as "oxygen ear," or middle ear oxygen absorption syndrome, which occurs following breathing an oxygen-rich gas during a dive. The middle ear may still be filled with oxygen, and the tissues surrounding the area metabolize the oxygen. The volume of gas slowly decreases as the oxygen is metabolized, making a pressure imbalance between the outer and middle ear. Generally, divers can continue to clear this pressure differential after the dive, without incident. Astronauts often experience "oxygen ear" for the same reasons. Most often it is following their training flights in the T-38 or space walks.

Aquanauts and astronauts exemplify the human spirit of exploration. The astronaut core at NASA includes just two professional divers: Dr. Michael L. Gernhard, a former commercial diver (mentioned above); and Capt. (select) Heidemarie M. Stefanyshyn-Piper, a Navy diving officer.

The current core of NASA astronauts shows that more than 50 percent are serious swimmers or qualified civilian divers who "enjoy diving" for sport. The overriding consensus seems to be that aquatic adaptability is a prerequisite to success as an astronaut. No individual possesses all the traits necessary to be the "perfect astronaut." Some aquanauts are better at rigging and can maneuver effortlessly through the water, while others are more dexterous and can handnet fish. Similarly, some astronauts are better at space-walking and others are better at operating the orbiter's arm.

The key seems to be the right combination of the people who balance one another's strengths and weaknesses to form a team with "all the right stuff." Aquanauts are the best-equipped group to transcend

the depths of the ocean and ascend to the heights of space. Selecting aquanauts for space flight missions is a more poignant pathway to success and increases the chances of a triumphant team.