Chapter 4

The Invention and Diffusion of Neutral Buoyancy Training*

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Abstract

This chapter will describe EVA underwater training and conclude by briefly describing the process of diffusion to the Soviet Union/Russia, Europe, Japan, and China.

Training for extravehicular activity (EVA) underwater is now normal technology; centers have been built in all of the major spacefaring countries and regions. But space historians until recently have given very little attention to how this small technological system, as we term it, came into existence and spread internationally.[1] Neutral buoyancy training was simultaneously invented in several places in the United States between 1963 and 1965, both within NASA and in large aerospace corporations. But the corporate activity did not survive beyond the end of the 1960s, whereas two training centers arose at the space agency in Houston and Huntsville. The Houston tank came out of NASA Langley's funding of a small Maryland company, ERA, which trained Edwin "Buzz" Aldrin (he legally changed his name much later) for the last Gemini mission, after earlier

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inventing the basic techniques. The Huntsville tank came from homegrown underwater experiments for what eventually became Skylab. By 1969, facilities were in operation at both centers. NASA thus was the effective inventor, in two parallel cases, of neutral buoyancy training. The technique spread internationally after 1980, when the Soviets completed their Hydrolab at Star City in Russia. Especially since 1990, further centers were built by Japan, Europe, and China.

I. Origins and Invention

Underwater experiments to assess the effects of "weightlessness," "zero gravity" or "zero G" (the most typical terms used in the early days of spaceflight), go back to the origins of space medicine in the 1950s and early 1960s. But such experiments were confined to physiological examinations of the impact on the human body of prolonged periods of low gravity. When the United States and the Soviet Union first created human spaceflight programs in 1958/59, long-duration zero-G was not an immediate problem, nor was leaving the spacecraft on an EVA, which was not even possible in the Mercury and Vostok programs. Just getting a human into orbit was challenging enough. Any training for leaving the spacecraft could be postponed to the second-generation craft that would follow. In any case, space program officials widely assumed that flying parabolas in zero-G aircraft would be the primary training method. In the United States at least, frictionless air-bearing surfaces became a second possibility. One was put into operation at the new NASA Manned Spacecraft Center (MSC) in Houston, Texas, in time to train Edward White for the first US EVA on Gemini IV in 1965. A year earlier, Mercury astronaut Donald "Deke" Slayton, who was now Director of Flight Crew Operations, did propose that astronauts in "SCUBA" suits simulate EVA in the water egress training tank, but this idea went nowhere for reasons not documented. (SCUBA is an acronym for "self-contained underwater breathing apparatus," but the lower-case form is now accepted.)[2]

In the United States, neutral buoyancy work arose outside MSC and the astronaut training program, first in the aerospace industry and then in other NASA centers. The pioneers appear to be engineers at Boeing in Seattle, Washington, who began experimenting in 1963 in scuba suits in Angle Lake next to a house owned by one of them. Spacesuit tests followed. The context was Boeing's involvement in the military X-20 Dyna-Soar spaceplane, soon cancelled, but the company's Bioastronautics Organization went on to formalize the experiments as Project OGER (for zero-G Effects Research) and build an 7.6 m (25 ft.) diameter tank in 1964. Boeing was probably speculating on its possible role in future military and civilian space station programs, but was also the first to abandon its neutral buoyancy facility, in 1967, presumably for lack of contracts. Other companies got into the act between 1964 and 1966, notably Convair/General Dynamics in San Diego, California; Garrett AiResearch in Los Angeles, California; and General Electric (GE) in Valley Forge, Pennsylvania.[3]

GE created the most elaborate corporate program, in large part because it got the contract for integrating the laboratory portion of the Manned Orbiting Laboratory (MOL) that replaced the X-20 as the US military's "manned" space program. (MOL was essentially a cover name for an astronaut-operated reconnaissance satellite.) In 1965, the company rented a public aquarium in Philadelphia more than once, then built an outdoor facility in the US Virgin Islands, where large wire-mesh mockups were submerged in the Caribbean. GE hoped to get contracts for a new NASA station program, which later evolved into Skylab, as well as continuing work on MOL. A special feature of the GE program was its use of water-pressurized suits, which eliminated most of the heavy weights needed to neutralize the air-pressurized suit's tendency to float like a balloon on the surface of the water. (The helmet was on a separate air circuit.) But the cancellation of MOL in mid-1969 spelled the end of the General Electric program; the other corporate neutral-buoyancy facilities and programs seem to have ended with the NASA and defense budget cutbacks at the time. The elaborate US corporate neutral-buoyancy activity of the 1960s seems to have left no legacy except technical reports. Effectively, the big aerospace companies played no role in the invention of neutral buoyancy as a human spaceflight training and simulation method.[4]

Instead, the real origins go back to a small project that began at NASA's Langley Research Center (LaRC) in 1964. It arose out of a study contract for a small preliminary space station in 1963. One of the contractors assisting LaRC was a tiny Baltimore, Maryland, company called Environmental Research Associates (ERA), founded by two entrepreneurs with engineering and science backgrounds, G. Samuel Mattingly and Harry Loats. In a meeting in early 1964, Mattingly pointed out that the station had no airlock. That led to a discussion of how difficult it would be to enter, exit, and turn around inside an airlock in weightlessness. The Space Station Research Group lacked the money to fund zero-G aircraft experiments, so it gave a contract to ERA to examine the problem in swimming pools. After receiving training at the Navy's pressure-suit school near the Hampton, Virginia, NASA facility, Mattingly and Loats experimented in the officers' club pool on the Air Force side of the Langley base, watched by their primary contract monitor, Otto Trout. But there were too many interruptions. They proposed that they take the clear plastic airlock mockup Langley had built to the Baltimore area and find a pool to work in. The Navy lent them two Mark

IV Mod 0 "Arrowhead" full-pressure suits as well. These were like NASA's Mark IV-based Mercury spacesuit, but had bellows joints to make movement easier.[5]

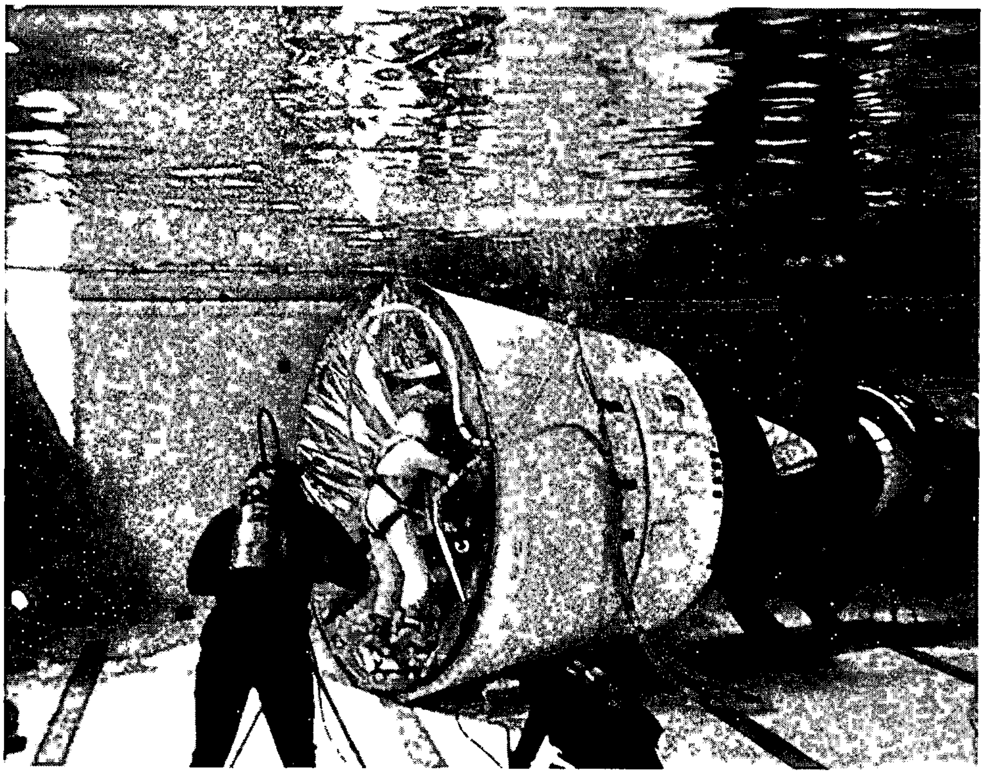

Figure 4–1: Buzz Aldrin practices for his Gemini XII EVA in a school pool outside Baltimore, Maryland. Environmental Research Associates ran the training exercise. (NASA photo).

Mattingly quickly made an arrangement with the private McDonogh School near ERA's office northwest of Baltimore, as he knew the water clarity was good from installing equipment in a previous business. The pool would be rented on an hourly basis, working around the class and swim team schedule, mostly evenings, early mornings, and school holidays. In mid-July 1964, tests began at McDonogh with the clear plastic airlock mockup. For the first report in September, Mattingly and Loats also did 1-G tests, and Mattingly arranged experiments in a zero-G aircraft at Wright-Patterson Air Force Base in Ohio. He felt that, since the aircraft method of simulation was viewed as the standard for weightless experiments, they had to include it for comparison purposes. In terms of hourly cost, pools were much cheaper and much longer durations were possible than the thirty seconds or less of weightlessness in an airplane. The drag produced by water was relatively insignificant for the slow movements that the test subject would make in a pressure suit. Trout and his superior at Langley, Paul Hill, were sufficiently impressed with ERA's results to extend its contract several times, through 1965 and into 1966.[6]

During this period, Mattingly and Loats invented all the elements of a neutral buoyancy technological system, much of which was empirical or relatively low technology. They hired young scuba divers at the only dive shop in the Baltimore area. Through trial and error, they discovered how and where to load weights to make an air-pressurized suit neutrally buoyant in all axes and directions of movement. Periodic rebalancing was needed due to water absorption in the cover layers. They modified the suits to use air instead of pure oxygen, to prevent toxicity effects, and rigged up scuba air tanks to the suits. Later, when they were working with the Gemini program, they installed tanks on the pool deck attached to the umbilical, just as was the case in Gemini EVAs. A lot of the lessons learned involved the creation of a rigorous safety culture. Accidents with the loss of suit integrity taught the ERA founders to have at least two divers present when anyone was working in the pressure suit. The invention of neutral buoyancy was thus not the invention of a new technology as such; rather it was the creative melding of existing technologies, small modifications, empirical procedures, and a safety culture into a new, small technological system that could be scaled up as needed.[7]

Even as ERA was quietly working for Langley in the McDonogh pool, all but ignored by the rest of NASA and the aerospace industry, Marshall in Huntsville, Alabama, began to develop its own neutral buoyancy project. Like Boeing and perhaps other early groups, it began with the individual initiative of engineers who were scuba enthusiasts, Charles Cooper and Charles Stokes of the Manufacturing Engineering Laboratory. Not long after the first US EVA by White in June 1965, Cooper and Stokes tried diving in the smaller of two open, no-longer-used, underwater explosive-metal-forming tanks. They worked with simulated objects from a Saturn S-IVB stage that were to be recovered in orbit on a projected spacewalk. These tasks were to lead toward the on-orbit refitting of a used Saturn IB S-IVB as a preliminary space station, the so-called "wet workshop" of the Apollo Applications Program (AAP). (After much evolution, it would morph into the "dry" Skylab station launched by a Saturn V.) Cooper and Stokes experiments led to a formalization of neutral buoyancy work in the winter of 1965/66. They trained in the Arrowhead suit. The larger 7.6 m (25 ft.) tank was fitted with a tent-like covering structure, heating and lighting, and went into formal operation in July 1966, while plans were formulated for a much bigger, permanent facility. The Marshall group seems to have learned the empirical lessons largely on its own, which explains its apparent lack of interest in ERA's work. But the Huntsville center also had a reason to keep its work quiet: rivalry with Houston over roles and missions in the human spaceflight program made it reluctant to tell anyone what was going on.[8]

Back in the Baltimore area, ERA struggled in spring 1966 to stay in business. Mattingly's sales trips to NASA Headquarters, MSC, and other places had not resulted in new interest. Houston's leadership felt that they just did not need it to train astronauts, an overconfidence fed by the lack of any EVA experience other than the deceptively easy spacewalk of White. Even Langley may have felt that ERA's work in a rented pool was limited, because it apparently gave a contract to Garrett AiResearch, which had built a larger tank in Los Angeles. In the hope of scaring up new work, on 15 June 1966 Mattingly and Loats staged a demonstration for NASA representatives of a task from the AAP Orbital Workshop, the removal of the dome cover of the S-IVB liquid-hydrogen tank. Cooper from Marshall attended but apparently was not impressed.[9]

The stroke of luck was that Don Jacobs of MSC was there. Ten days earlier, during a nearly disastrous EVA on Gemini IX, Eugene Cernan had become dangerously overheated and exhausted because of the unanticipated workload of fighting the pressurized suit and the laws of physics, since he lacked adequate handholds and footholds to restrain movement. A much better suit cooling system was needed, but so was a better understanding of how to work in weightlessness. Jacobs immediately gave ERA a contract extension to evaluate a task from Michael Collins' Gemini X EVA scheduled for mid-July. Mattingly and Loats' team did the simulation and showed that it would be difficult, but the information came too late to be of any use in a program that launched a crew every other month.[10]

The real breakthrough came in July. Cernan went to McDonogh, first to observe and then to run a full simulation of his very difficult EVA task of donning an Astronaut Maneuvering Unit (AMU). The 28–29 July work demonstrated the fidelity of neutral buoyancy to his actual EVA. Days earlier, MSC Director Robert Gilruth had already issued a memorandum instructing his center to incorporate neutral buoyancy training at ERA as a step towards creating a facility at Houston, if possible by the end of the year. He assigned Mercury astronaut Scott Carpenter, much involved in undersea exploration, as his special assistant on the issue. Gilruth had recently heard a pitch from GE regarding its capability, but chose ERA, which had a convenient contract arrangement with NASA through Langley. It is unknown whether the Baltimore group's use of air-pressurized suits rather than water-pressurized ones influenced him, but it was certainly closer to actual EVA experience. Cernan returned to Houston four or five days later and reported the validity of neutral buoyancy as an EVA simulation, reinforcing its newfound acceptance in the Astronaut Office.[11]

ERA got a new assignment to evaluate EVA tasks for Gemini XI, scheduled for launch in mid-September, but again, the report came too late to help the spacewalker, Richard Gordon. He too became exhausted and had to cut short his EVA. However, there was time to train Buzz Aldrin for Gemini XII, the last flight in the program. Aldrin came at the time of Gemini XI to evaluate new procedures for donning the AMU—also to be his task. But NASA's leadership soon thereafter decided to delete it as too challenging. Aldrin was given a simpler set of evaluative tasks regarding handholds, footholds, tethering, and elementary tool work, much to his disgust. But he ran a full simulation of the EVA in October, attended by his commander, James Lovell, and high NASA officials, and successfully carried out his EVAs in space in mid-November. Sam Mattingly sold Houston on one more evaluation. Aldrin returned in early December to demonstrate the correspondence between neutral buoyancy and his actual experience.[12]

Meanwhile, ERA had also gotten a contract to evaluate the S-IVB dome cover removal job, thanks to a combination of Houston's new interest in underwater simulation and training, and the growing awareness of the difficulty of removing seventy-two bolts. Alan Bean, recently assigned to head AAP in the Astronaut Office, went into Marshall's tank in early September and participated in a dome removal simulation. In October, Scott Carpenter attempted the same task in the McDonogh pool with the ERA group and removed only one or two bolts in over an hour. MSFC and MSC quickly agreed to evaluate a new "quick-opening hatch" for the S-IVB liquid hydrogen tank.[13]

II. Facility Construction and Diffusion

During three months, neutral buoyancy work had gone from marginal to central in NASA's human spaceflight program. But ERA's primacy was very short-lived. Gemini was over and Houston was now determined to have its own facility. MSC moved the 6 m (20 ft.) diameter water-egress training tank from Ellington Air Force Base to Building 5 and converted it to underwater EVA work, although that took much longer than anticipated. Mattingly himself noted the tendency to dismiss the complexity of the system: "It's only a tank of water" was his summary of that attitude. After difficulties finding enough scuba-trained personnel and getting the equipment to work, the facility officially came into operation in August 1967. ERA served as consultants, but found itself hamstrung by new safety rules imposed in the wake of the Apollo fire that killed three astronauts at the end of January. Contracts with NASA dwindled. Eventually the company moved on to other NASA studies but folded in the early 1970s.[14]

At Marshall, the permanent facility finally was built in 1968 and put into operation the next year. At 23 m (75 ft.) in diameter and 13 m (43 ft.) depth, the Neutral Buoyancy Simulator (NBS) dwarfed anything else built for some time. Development work on the 7 m (23 ft.) diameter Orbital Workshop that became Skylab drove this investment. Von Braun famously hid this construction from Headquarters by classifying it as a "tool" rather than a "facility," provoking a government investigation. The NBS proved invaluable for development, but also for astronaut training for Skylab, including the development of the rescue techniques used in 1973 to salvage the station after it arrived in orbit in damaged condition. During the shuttle program, the NBS continued to be valuable, notably for the size that allowed a full-scale section of the Hubble Space Telescope and other large payload simulators that could be accommodated in it. Houston resented the duplicative nature of Huntsville's facility during lean times of budget competition, and tried to get it closed, but at other times appreciated its larger capacity. It was not until Houston's third pool came into operation in 1997, the gigantic Neutral Buoyancy Laboratory, that the NBS was finally shut down.[15]

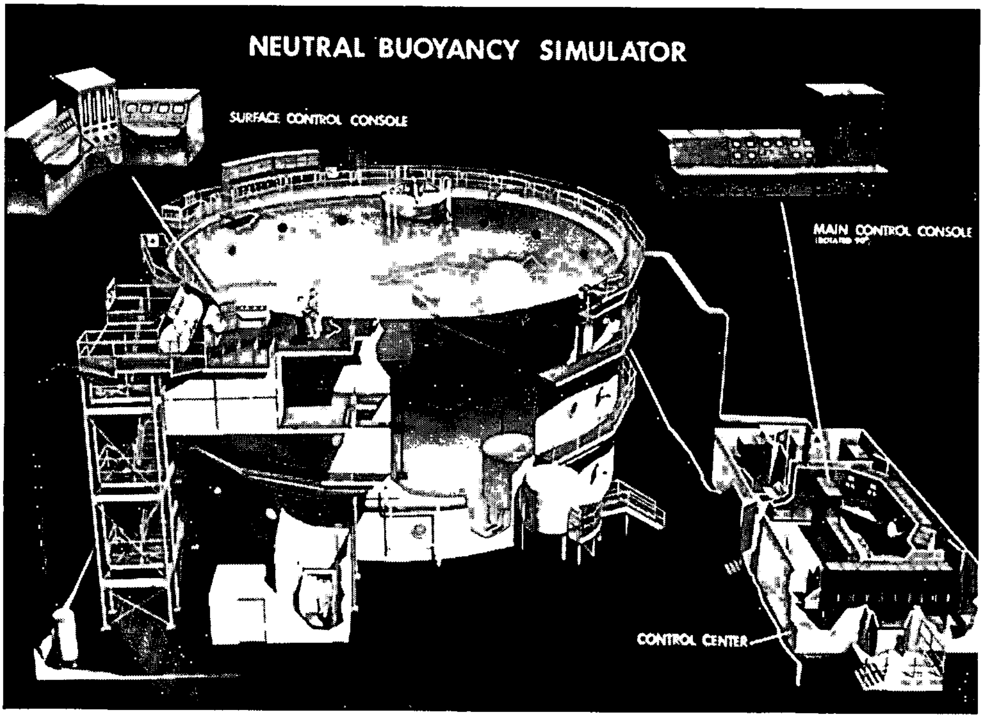

Figure 4–2: Marshall Space Flight Center Neutral Buoyancy Simulator cutaway. (NASA photo).

MSC (after 1973 the Lyndon B. Johnson Space Center) used its Water Immersion Facility (WIF) for Apollo EVA training, both zero-G and lunar 1/6-G. But for the shuttle a larger pool was required. The Weightless Environment Training Facility (WETF) opened in 1979 with a rectangular pool, rather than a cylindrical tank, as it was designed to hold a full mockup of the shuttle payload bay. It was 24 m (79 ft.) in length, 9.8 m (32 ft.) in width, and 7.6 m (25 ft.) deep, containing 1.82 million liters (481 thousand gal.) of water maintained at 31°C during operation. It was critical to shuttle EVA development and training, but eventually it was too small for multiple ISS modules and the training needed to master the massive number of EVAs required for station assembly. The NBL is 61.6 m (202 ft.) long, 31 m (102 ft.) wide, and 12 m (39 ft.) deep and holds 28 million liters (7.4 million gal.) of water. The water filtration systems, bridge cranes, lighting and heating systems are gigantic, as fits the scale of the facility, which is housed in the Sonny Carter Training Facility on the grounds of the former Ellington Air Force Base.[16]

The Soviet Union did not open its facility, the Hydrolab at Star City, until the late 1970s. According to Asif Siddiqi, the Soviet Air Force had an entrenched interest in the zero-G aircraft and felt that method was adequate for the short EVAs undertaken in the program in the 1960s. But the visit of the Soyuz 9 cosmonauts Andrian Nikolayev and Vitaly Sevastyanov to Marshall's NBS on 21 October 1970 influenced them to argue successfully for neutral buoyancy in the USSR. Sevastyanov donned an Apollo suit, along with Apollo 9 (and Skylab backup) astronaut Russell Schweickart, and participated in a simulation of a Skylab maintenance task. The Soviet space program leadership made a decision shortly after the cosmonauts' return, leading to construction beginning in 1974/75, but problems delayed completion. Another pool was used to train for EVA on the military Salyut (Almaz) missions 3 and 5. The Hydrolab was first used by cosmonauts on 29 December 1978 and declared fully operational on 1 March 1980. The cylindrical tank, at 23 m (75 ft.) in diameter and 12 m (39 ft.) deep, is almost identical in dimensions to Huntsville's, which seems likely to be no coincidence. It has been crucial to Salyut, Mir, and ISS EVA training.[17]

In the 1980s and after, neutral buoyancy facilities appeared around the world, including in corporate and academic contexts. The demands of ISS in particular have led to the construction of facilities connected to the Japanese and European space programs to prepare for, and then train for the Kibo and Columbus modules. The Japanese laboratory at Tsukuba came into operation in the mid-1990s and development of modules has led to the creation of permanent facilities in Turin and the European Astronaut Centre in Cologne. In about 2008, the Chinese opened a neutral buoyancy lab at its astronaut training center outside

Beijing. Unfortunately, the Japanese tank was damaged in the earthquake of March 11, 2011, and was dismantled in early 2012.[18]

In sum, neutral buoyancy training and simulation has gone from a marginal idea rejected or ignored by the US and Soviet programs to a central and normal training and development technique for EVAs in weightlessness all over the world. Although it was invented in the mid-sixties, most importantly by two different groups working for or within NASA, it was not a new technology as such. Rather it was (and is) an assemblage of selectively modified, existing technologies such as swimming pools, pressure suits, and scuba equipment, combined with empirically learned rules and a strong safety culture. As such, neutral buoyancy is really a technological system, not a single technology. In view of its limited scale compared to large technological systems like human space programs it is embedded in, is best called a small technological system. In any case, whatever the terminology, there is no doubt as to importance of neutral buoyancy training to the human exploration of space.

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