Feature Endeavour Vol. 39 No. 3–4

Practicing for space underwater: inventing neutral buoyancy training, 1963–1968

Michael J. Neufeld[a,*] and John B. Charles[b]

[a] National Air and Space Museum, Smithsonian Institution, Washington, DC, USA
[b] Lyndon B. Johnson Space Center, National Aeronautics and Space Administration, Houston, TX, USA

Neutral buoyancy's value was far from obvious when human spaceflight began in 1961. Starting in 1964, Environmental Research Associates, a tiny company in the suburbs of Baltimore, developed the key innovations in an obscure research project funded by NASA's Langley Research Center. The new Houston center dismissed it until a mid-1966 EVA crisis, after which it rapidly took over. In parallel, NASA Marshall Space Flight Center developed many of the same techniques, as did many large aerospace corporations, yet the long-run technological impact of corporate activity was near zero. Because ERA and Marshall's pioneering activities led to the two long-running NASA training centers at Houston and Huntsville, those two organizations deserve primary credit for the construction of the neutral buoyancy technological system.

Almost every day, somewhere in the world, astronauts or cosmonauts are practicing for EVA (extravehicular activity or 'spacewalking') underwater. At the Neutral Buoyancy Laboratory of the Lyndon B. Johnson Space Center in Houston, TX, crewmembers rehearse procedures in a gigantic, 6-million-gallon (23-million-liter) pool holding full-size mockups of multiple modules of the International Space Station (ISS). Opened in 1997, it superseded earlier tanks built at the National Aeronautics and Space Administration's premier human spaceflight centers. Russian cosmonauts train at the Hydrolab in Star City, outside Moscow, a large facility built in 1980; European Space Agency astronauts work in Houston, and also at their own tank at the European Astronaut Centre, Cologne, Germany; Japanese astronauts at the Tsukuba Space Center near Tokyo. China recently opened a facility at the Chinese Astronaut Research and Training Center in Beijing, to prepare for EVAs from its Shenzhou spacecraft and Tiangong stations.[1] In short, 'neutral buoyancy training' (so-called because the spacesuited astronauts are weighted to be neutrally buoyant, simulating weightlessness) has become normal technology. Indeed, it is absolutely critical to the success of numerous human spaceflight programs. Assembling the ISS, or repairing the Hubble Space Telescope, would have been impossible without it.

Neutral buoyancy's value was far from obvious when human spaceflight began in 1961, however. NASA at first took no interest in training its astronauts this way. Beginning in 1964, Environmental Research Associates (ERA) a tiny company in the suburbs of Baltimore, MD, developed the key innovations in an obscure research project funded by NASA's Langley Research Center (LaRC) in Hampton, VA. The new Houston center (then named the Manned Spacecraft Center or MSC) dismissed it until a mid-1966 EVA crisis, after which it rapidly took over. In parallel, NASA Marshall Space Flight Center (MSFC) in Huntsville, AL, developed many of the same techniques, as did many large aerospace corporations. Some, notably Boeing and General Electric, made large investments in neutral buoyancy, and experimented with an alternate suit technology, yet the long-run technological impact of that major corporate activity was near zero. Because ERA and Marshall's pioneering activities led to the two long-running NASA training centers at Houston and Huntsville, which in turn influenced other space agencies, those two organizations deserve primary credit for the construction of the neutral buoyancy technological system.

We have chosen the term *technological system* because neutral buoyancy was invented in the 1960s less as a new technology than as an assemblage of existing technologies, tacit knowledge, and safety practices. In technological systems theory, originating from the work of Thomas P. Hughes, the term has been confined almost exclusively to large systems like electrical power networks and military-industrial projects. On this model, NASA's human spaceflight complex can be considered a technological system, and the EVA problems that arose in the mid-1960s, to use Hughes' military metaphor, were a *reverse salient* that required organizational and technological fixes. But no fundamentally new technological devices were required to construct neutral buoyancy training, although some local and specific innovations were needed. Rather, local innovators and *system builders*, to use another Hughesian term, assembled existing, often commercially available technologies like scuba equipment, full-pressure suits, cameras and swimming pools, and matched them with

Corresponding author: Neufeld, M.J. (neufeldm@si.edu).
*Tel.: +1 202 633 2434.
Available online 15 July 2015

the experienced-based cultures needed to make neutral buoyancy workable and safe. As a concession to the differences in scale, neutral buoyancy could perhaps be called a *small technological system*, a sub-component of a larger system.[2]

The events that led to this critical innovation have only begun to emerge recently in popular accounts and have never been subject to scholarly examination. The older official NASA histories and key astronaut memoirs barely mention neutral buoyancy's origins and often inaccurately, while a recent semi-popular history by David J. Shayler, *Walking in Space*, gives a partial account of the Baltimore story in a few paragraphs.[3] The full dimensions of the ERA story began emerging after 2012 in popular articles written by, or in the cooperation with, the surviving founder of the company, G. Samuel Mattingly, who died in November 2014.[4] Marshall's early work has scarcely been treated at all, and when it has, authors have mostly noted MSFC Director Wernher von Braun's stealthy construction of a giant tank in Huntsville through a legally dubious end-run around the NASA procurement system in the late 1960s.[5] Due to scant surviving documentation, the Marshall story remains difficult to tell, in contrast to somewhat richer material on ERA, but this article will attempt to examine both stories and draw some conclusions about the contingent and improvised creation of the neutral buoyancy technological system.

The problem of weightlessness

'Weightlessness,' 'zero-gravity' and 'zero-G' are the terms most often used to connote the state of freefall experienced during orbital or coasting flight in space. ('Microgravity' is now the usual technical term – denoting the microscopic accelerations that exist even while floating in an apparent absence of gravity.) The existence of this phenomenon was well known in early space advocacy and science fiction, but was mostly wished away with devices like magnetic shoes and rotating space stations. After World War II, however, it gradually became an area of concern for the new discipline of space medicine, growing out of aeromedicine as rocket and jet aircraft entered service and human spaceflight became more and more imminent.[6]

In the United States, the formation of NASA out of the National Advisory Committee for Aeronautics (NACA) in fall 1958 and the simultaneous creation of one of its first programs, Project Mercury, made the impact of weightlessness on astronaut performance suddenly a real question. Foremost was simply the ability to perform in a cockpit while weightless. Some physicians conjured frightening scenarios of basic human functions like sight and swallowing failing, which contributed to engineering decisions to make the first U.S. human spacecraft, Mercury, to be largely automated. (Its Soviet counterpart, Vostok, was entirely automated, and required a special override code to unlock the controls.) Leaving the capsule and performing work in space was not feasible and preparations could be put off until a later program.

From the origins of space medicine, it was obvious to researchers that water immersion was one possible way to simulate weightlessness. Among the many physiological experiments conducted were ones by Dr. Duane Graveline of the School of Aerospace Medicine at Brooks Air Force Base in San Antonio, TX in the early 1960s. He had subjects in scuba wetsuits and aviators' full pressure helmets spend extended periods of time underwater in a specially constructed tank.[7] Informal experiments with scuba-equipped divers probably were the first attempts to simulate EVA work underwater, but these have been largely undocumented. (The Aqualung, invented in World War II occupied France by Jacques Cousteau and Émile Gagnan, was the breakthrough that made scuba, an acronym for 'self-contained underwater breathing apparatus,' feasible.)

For NASA, it was not a concrete problem until the Mercury program ended in 1963 and managers needed to formulate training plans for the two-man Gemini spacecraft, which would demonstrate key objectives, including EVA, needed for the Apollo lunar landing goal set by President John F. Kennedy in 1961. On January 30, 1964, Mercury astronaut Donald K. 'Deke' Slayton, who had become MSC Assistant Director of Flight Crew Operations after he had been medically disqualified for spaceflight, issued a Gemini EVA training plan. It is noteworthy as much for what did not happen as did. He quickly dismissed weightlessness in aircraft flying parabolas (which is not a simulation, but actual freefall for some seconds as the aircraft coasts over the peak in its trajectory). Instead:

> The only practical means of simulating the overall effects of reduced gravity for relatively long periods of time is by water immersion. A fairly realistic simulation of some of the techniques and problems in accomplishing extra-vehicular activities can be accomplished by submerging the Boilerplate #201 in the Ellington tank. The flight crews can then don SCUBA equipment and practice such tasks as egress, ingress, opening and closing the spacecraft hatches and maneuvering over the spacecraft.[8]

MSC used a water tank at nearby Ellington Air Force Base, outside Houston, to train astronauts to make ocean exits out of their spacecraft. Boilerplate #201 was the first Gemini simulator, only recently delivered for water-tank and open-water training exercises. It was intended for use in rough water and even inverted and partially submerged, so full immersion would not have been impractical.

Yet Slayton's suggestion was discarded for reasons not documented in surviving MSC records. He does mention another new tool: frictionless, air-bearing surfaces, in which an astronaut would stand or be placed on a disk generating an air current above a very smooth surface. In theory, it was a 'five-degrees of freedom' simulator (the only dimension of movement missing would be vertical to the surface), but in practice the astronaut could move about on the floor in only one body orientation at a time. Such a simulator came into service at MSC in 1965, but it appears to have been useful only for practicing with handheld maneuvering guns or jetpacks.[9] Aircraft zero-G training became the primary method; 'water immersion' was ignored. Perhaps the need to train all astronauts in scuba, or the lack of realism of training in diving gear, as opposed to a pressurized spacesuit, were inhibitors. And NASA was already using an Air Force KC-135 zero-G training aircraft (the military precursor of the Boeing 707 airliner), which could create several-dozen thirty-second weightlessness periods on a single flight. The downside was that between each of these was a 2-G pull-out at the bottom of the dive. This constant up-and-down motion quickly earned it the nickname 'the vomit comet.'[10]

Early ERA work with Langley

Rather than at Manned Spacecraft Center, NASA's original experiments in neutral buoyancy arose in early 1964 almost by accident at Langley. Through much of its history it had been primarily an aerodynamic institution. When NACA became an operational space agency, new centers arose (including MSC out of Langley) that were to carry out rocket and spacecraft programs, while LaRC remained focused on research, now with a larger space component. The tidewater Virginia center had been conducting space station studies with aerospace contractors since NASA began, but the huge technical and financial challenge of Kennedy's Moon goal meant the agency had to postpone an Earth-orbiting station, possibly into the seventies. Langley scaled back its ambitions in 1962/63 to a smaller, non-rotating, cylindrical Manned Orbiting Research Laboratory (MORL). It let study contracts with Boeing and Douglas and ultimately selected the latter to refine the concept.[11] But Langley also did a lot of in-house research and worked with small contractors on technical details. One of them was Environmental Research Associates in Randallstown, MD, in the northwest Baltimore suburbs.

Two technical entrepreneurs in their thirties with partial engineering and science educations, G. Samuel Mattingly and Harry Loats, formed ERA around 1962 (Figures 1 and 2). They had earlier worked together at a Baltimore-area company specializing in aerial refueling. From their knowledge of hoses and reels, they had sold Langley and the Gemini Project Office on the idea of 5000-ft. tether for an astronaut working outside the spacecraft, at a time when EVA concepts were very inchoate. That had been routed through a major contractor, Marquardt, but a 1963 contract to examine seals and sealants for the station was direct. When Mattingly's LaRC contacts briefed them on the station, presumably MORL, he noted that it had no airlock. It was an old idea in science fiction: a chamber that could be depressurized and pressurized, allowing passage outside without losing too much cabin atmosphere. Challenged to produce a concept, Mattingly, a self-described 'space nut' who had been a Buck Rogers fan in his youth, claims he said: 'Well, it's just a thing four feet in diameter, . . . six feet long, and it has a door on either end and one cut in the side.'[12]

Their primary contract monitor, Otto Trout of the Space Station Research Group, had the model shop build a clear plastic cylinder of those dimensions, with three wooden hatches: two circular and one oval one at one of the ends. A picture of it dated to January 1964 shows two spacesuited, unpressurized subjects working in 1-G conditions to test a hatch. That same month, ERA began a new contract on

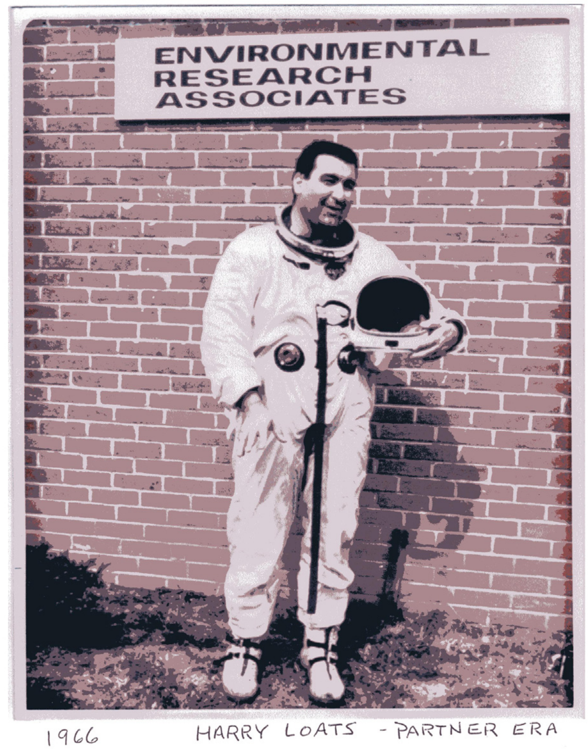

Figure 1. Harry L. Loats, Jr., co-founder of ERA, in a Gemini spacesuit in 1966. Courtesy of Sam Mattingly.

'The Study of the Performance of an Astronaut During Ingress-Egress Maneuvers Through Airlocks and Passageways.' Just looking at the mockup, according to Mattingly, raised questions about the ease of turning around inside an airlock of that size while wearing a pressure suit under weightless conditions. It was obvious that normal gravity conditions would not be a meaningful test.[13]

Lacking access to a zero-G aircraft, Trout, Mattingly and Loats quickly thought of immersing the airlock in water. In order to do that, the ERA personnel first had to be trained in pressure suit safety. Mattingly knew the nearby naval air station from their aerial refueling days, so

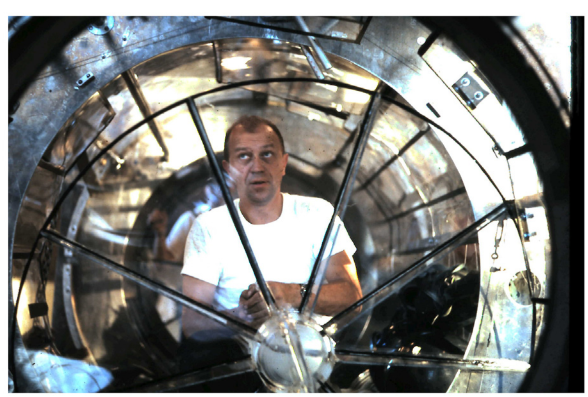

Figure 2. G. Samuel Mattingly, ERA co-founder, in the Orbital Workshop mockup in 1966.
Courtesy of Sam Mattingly.

one day they went over unannounced to find the Navy's pressure suit school. The trainers there subsequently put them through the vacuum chamber, including an explosive decompression at the equivalent of 70,000 ft and the dunking device, which trained pilots to exit a crashed aircraft at sea upside-down underwater in a full pressure suit. Mattingly qualified on 2 June 1964, and was given a membership card in SPACE, the half-jokingly titled Society of Pioneering Astronauts and Celestial Explorers.[14]

Shortly thereafter, Mattingly, Loats and Trout got to use the officers club swimming pool on the Air Force side of the base for a single afternoon. They filmed some tests in the airlock mockup, but visitors frequently interrupted them to ask what was going on or to offer to help. It was clear that this was no long-term solution. The two proposed to Trout that they take the mockup to Baltimore and set themselves in a pool up there. He readily agreed and they put it on the back of their little Volkswagen truck and drove off.[15]

In a continuation of the very informal culture of the time, in which the space race with the Soviet Union was paramount, the Navy's school allowed them to borrow a couple of Mark IV Mod 0 'Arrowhead' full pressure suits with no documents signed or questions asked, if Mattingly's memory is correct. (Presumably Trout or someone from Langley verified or could verify the legitimacy of their contract.) The Mercury spacesuit had been a modified Navy Mark IV. The Arrowhead version incorporated bellow joints, which allowed a little better movement in a garment originally meant just to protect a pilot in a seated position. The joints minimized the volume change that took place while moving the limbs, but every movement in the pressurized suit was a battle against its tendency to be rigid: the wearer was inside the inflated balloon of the rubber pressure bladder. Mattingly notes that when they put him the altitude chamber, at 70,000 ft the exterior of the suit felt 'like a rock.'[16]

From selling pool equipment in a previous business, he knew that the filtration system was particularly good at the McDonogh School, a boy's military institution not far from ERA's 'little $50-a-month office' in Randallstown. He quickly made a deal with the headmaster, Robert Lamborn, to rent the pool at the same rate as the Red Cross did for swimming lessons, as long as no equipment was left on the pool deck and activities were on a non-interference basis with the swim team and other scheduled uses. Photographs show that the first experiments in the transparent airlock mockup were made in the deep end of the pool on 18 July 1964. Under their contract, they began a systematic comparison of what it took to do the various tasks, on the ground and in the pool. The pressurization level of the suit, from one pound per square inch (PSI) over the external pressure up to 3.5, was another variable in timing the ability to perform various tasks (Figure 3).[17]

Thanks to Mattingly and Loats' connections with the Wright-Patterson Air Force Base outside Dayton, OH, from the flight refueling days, Mattingly and William Franz, a nineteen-year-old ERA scuba diver, also carried out comparative tests in a zero-G training aircraft. On 14 August 1964, Mattingly qualified with a ride on the KC-135 jet. Subsequently he and Franz did a day or two of

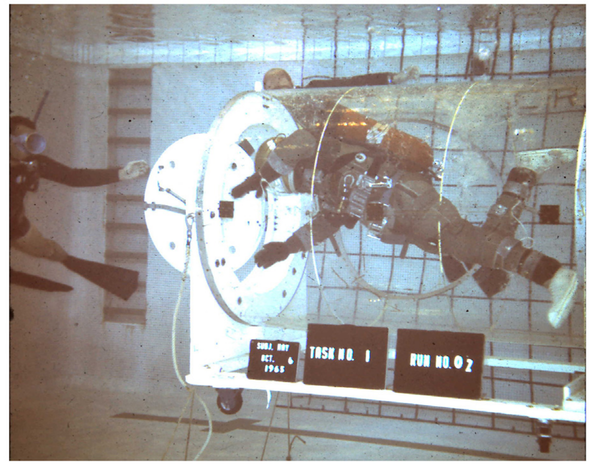

Figure 3. Neutral Buoyancy test in the McDonogh pool with the NASA Langley airlock mockup, October 1965.
Courtesy of Sam Mattingly.

tests in the old, piston-engine C-131B (a converted Convair 240 airliner), which was much easier to schedule than the 'K-bird.' Its periods of weightlessness only lasted 8–10 s and only a few parabolas could be done at a time. Mattingly felt that including the zero-G aircraft was politically important for the study, as it was viewed at the time as the baseline for weightless testing on the Earth. But he and Loats quickly came to the conclusion that it cost much more and delivered a less satisfactory simulation of EVA.[18]

ERA completed its first report on neutral buoyancy at the end of August. The study and the films made underwater sufficiently impressed Otto Trout's superior, Paul Hill, that Langley extended their contact. Underwater tests were repeatedly extended, through 1965 and into early 1966. ERA and Langley experimented with different size hatches. They may have also shrunk the mockup diameter to the point where it was no longer possible to turn around, valuable information for a potential spacecraft design. Harry Loats primarily handled technical report writing and Sam Mattingly the contracting relationships. Although fit and in their thirties, they found working in the pressure suit sufficiently strenuous that they gave it over to college-age scuba-diving enthusiasts they recruited at the only dive shop in the Baltimore area. Even then, only a couple readily adapted to the spacesuits; most acted as safety divers and help.[19]

It was during 1964–1965 that ERA assembled the technologies and practices that make up a working neutral buoyancy technological system. Much of it involved combining commercially available technologies with ones available on loan from the military or NASA: scuba tanks, regulators, wet suits and related equipment; full-pressure suits; still and movie camera equipment with waterproof housings made by ERA; and mockups produced by ERA or Langley. Mattingly and Loats modified the pressure regulators and air supply for the Arrowhead suits. They decided to use air instead of pure oxygen to avoid the oxygen toxicity effects that might set in on longer dives; they adapted scuba tanks to mount on the back of the suits.

In mid-1966, when Gemini work began, they created an umbilical connection to tanks on the pool deck, as this was the way almost all Gemini EVAs were carried out, with the astronaut connected to the spacecraft oxygen supply.[20]

A significant part of making neutral buoyancy work was simply learning from experience. A gas-pressurized spacesuit is a balloon; the wearer will float. The first lesson was the placement of weights to make the test subject neutrally buoyant in all six degrees of freedom (three axes of the body, and three directions of motion). In the Langley officers club pool, Mattingly noticed that he did not rise or fall, but with lead-weighted boots on, he tended to become vertical. In the McDonogh pool they started with bags of lead welding shot tied in various places on the suit and by trial-and-error learned how to make the suited subject neutral in all axes; later they adapted weights attached by belts and straps. It was an art, rather than a science. The ERA experimenters also discovered that after twenty minutes, the absorption of water by the spacesuit's cover layer would change the buoyancy, and so they had to incorporate periodic rebalancing into the schedule. They also noted the limitations of the simulation: movement through water created drag not present in a vacuum, but motion tended to be slow, so it did not make a significant difference. The suited subject also was not weightless inside the suit, even though he was neutrally buoyant, so working upside-down was particularly uncomfortable, as the blood still rushed to the head.[21]

Safety protocols were crucial. Scuba divers were limited to thirty minute sessions because of the dangers of hypothermia, even with pool water in the low seventies Fahrenheit. Most critical were emergency procedures for suit failure. With two hundred pounds of lead weights on, if the suit's integrity fails, the wearer could be going straight to the bottom of the pool. Mattingly and Loats experienced that early, when the latter was wearing a Mark IV and the former was in scuba gear.

> And the seal on his [Loats'] faceplate blew out, which means he gets hit in the face with a bunch of water. And I'm the only [one] there with him, and he can't move at all. So I grabbed him, I got behind him and got my head up under the tank, and I was swimming with everything I had, trying to make it go. Seemed like forever, and I finally got him to the point where his foot touched down [in the shallow end] and then his other foot moved, and I figured, 'Thank the Lord.'[22]

They needed more than one safety diver when anyone was working in the suit.

Bruce Tharp, a diver who began working for ERA in 1965, experienced a similar accident when he was working in an airlock mockup with another suited diver, George Hay, in the tight space. Hay accidentally 'kicks my air off, and the helmet just implodes with water.' Because the air's entry point was the Mark IV's helmet, with exhaled gases venting into the body through a check valve to pressurize the suit,

> it felt like somebody banging you in the stomach with a baseball bat, because three and a half pounds [suit pressure] ... was trying to force your stomach out through your mouth, and I was already out of breath because, of course, I was doing a lot of work.

Quickly, Hay's brother Steve, acting as a safety diver, stuck a scuba regulator in his mouth, 'which is the only reason I didn't drown.'[23]

Neutral buoyancy's origins at aerospace firms and NASA Marshall, 1964–1966

By 1966, several more organizations had independently developed their own versions of a neutral buoyancy technological system. At most, they were only dimly aware of ERA's work through conference presentations by Otto Trout or ERA representatives. Unfortunately, it is difficult to find out what happened at the aerospace firms, as they are infamous for not keeping records. Often the only evidence that survives is photographs, technical reports, and newspaper photos or articles that provide at least an occasional chronological reference. Marshall Space Flight Center's case is only slightly better documented.

Boeing in Seattle was probably the first aerospace company to experiment with neutral buoyancy, as it was the prime contractor for a military space plane called the X-20 Dyna-Soar. Engineers in its Bioastronautics Organization started before Langley and ERA, working with scuba equipment in Angle Lake in September 1963. They modified a spacesuit for use in the lake as well, and experimented well into 1964. Although Dyna Soar was canceled in late 1963, the company formalized the effort as Project OGER, for 0-G Effects Research, and built an elaborate Neutral Buoyancy Facility with a 25-foot-diameter (7.6 m) tank that was 20 ft (6.1 m) deep. Newspaper photos from December 1964 show suited subjects in the water in Arrowhead suits; and a technical report from August 1965 confirms that further work was done that year, notably on an airlock mockup 10 ft (3 m) long and 54 in. (1.37 m) in diameter. The Boeing facility was self-funded, apparently in the hope that the company would play a larger role in human spaceflight programs. But the pool was only in use for about two years because Bioastronautics closed in 1967, likely for lack of contracts.[24]

Convair/General Dynamics in San Diego and Garrett AiResearch in Los Angeles were two more West Coast aerospace firms working in neutral buoyancy. Lack of documentation makes it difficult to pin down when they began. There is a Convair picture from 1964 of a suited subject underwater, and subsequent work continued until at least 1969 under an Air Force contract; Convair built its own dedicated underwater test facility, presumably with company funds, in 1967. A 1967 Garrett technical report demonstrates that its work was being done under Langley contract in a 30 ft (9 m) diameter outdoor tank the company constructed at the AiResearch plant. The amount of work reported suggests that the study began in 1966. It covered astronaut maintenance and assembly tasks that appear too large to be handled by ERA in a rented swimming pool.[25]

General Electric's Valley Forge Space Technology Center, outside Philadelphia, mounted the most elaborate corporate neutral-buoyancy program. Under the leadership of Carl Cording and Theodore Marton, work likely started late in 1964, as in early 1965 the company rented the Philadelphia Aquarium's Aquarama facility. The tank had a windowed side for dolphin shows. The test group sank a mockup of interior laboratory areas of the Defense Department's Manned Orbiting Laboratory (MOL) spacecraft and carried out work tests with subjects in scuba gear. Later photographs also show spacesuits.[26]

MOL, the project that replaced Dyna-Soar in December 1963, was nominally to test the military uses of human spaceflight, but that unclassified purpose was – probably from the outset – a cover story for an astronaut-operated reconnaissance system codenamed DORIAN. GE bid for the main contract, but ended up as a major subcontractor to Douglas Aircraft for equipment inside the laboratory portion. Operating the KH-10 super-high-resolution telescopic camera was the two astronauts' main task, something that had to be avoided or disguised in open neutral buoyancy tests. MOL astronauts would have traveled to and from space in a modified Gemini capsule mounted to the top end of the cylindrical laboratory, and would have had to maneuver themselves in weightlessness through a narrow tunnel that ran from a hatch between the two ejection seats to the living and working quarters. That tricky maneuver also became part of GE's neutral buoyancy work, using wire-mesh mockups in new experiments at the Aquarama.[27]

Rather than investing in its own large tank, GE took a different approach. In 1966, it began building a facility at Buck Island in the U.S. Virgin Islands, where full-size mockups could be sunk in the clear, warm tropical waters of the Caribbean. This facility seems to have been motivated in part by MOL and in part by NASA's newest space station program, an Orbital Workshop to be created out of the refitted S-IVB stage of a Saturn IB. Marshall Space Flight Center in Alabama proposed this project in mid-1965; it had evolved from earlier 'spent stage' ideas for reusing the empty booster stage that would otherwise be abandoned in orbit. The Orbital Workshop became a central project of the Apollo Applications Program (AAP), which the NASA leadership created in August 1965 to find further uses for the Apollo-Saturn hardware built for the Moon landing. (AAP eventually shrank to Skylab, a single, fully outfitted S-IVB workshop orbited by a Saturn V in 1973.) The S-IVB had a diameter of 22 ft (6.7 m), which, if mocked-up at full scale, required a very large tank. GE invested its own money in the outdoor Buck Island facility, and sank a giant, wire-mesh Workshop mockup there in the winter of 1966/67. The only study contract from NASA for which there is any evidence is 'Design Criteria for Maintenance and Repair of Advanced Space Stations,' awarded in 1966 through the Office of Advanced Research and Technology at Headquarters, and administered by Marshall. It was renewed in 1967. Work on that contract was carried out at a water tank in Huntsville, but never in Buck Island. In 1967/68, GE also used the Virgin Island site for MOL simulation.[28]

There was one major difference in the neutral buoyancy system General Electric assembled: the water-pressurized suit. Using water to pressurize the main body of the suit meant that little weight was needed to achieve neutral buoyancy, and the suit was more comfortable for the wearer, since he floated inside it. Proper control of the water temperature also could increase comfort and reduce overheating. But it required either that the 'astronaut' wear a scuba mask and regulator inside an open helmet, which restricted vision, or put on a self-contained helmet with its own air circuit, which GE indeed invented, along with a backpack to circulate supply air and water to different suit ports. Moving the limbs was a less realistic simulation, however, as the wearer was pushing water around inside the suit. Air-pressurized-suit advocates also considered it less safe, as the water-pressurized one did not have residual air inside the body of the suit, if air to the helmet was cut off. While water-pressurization was in some ways more convenient, it was a less-accurate simulation of how an air-pressurized suit felt in weightlessness. Convair and Boeing experimented with water pressurization as well (it is unclear who developed it first), but it never spread to NASA's groups, which began with air pressurization and considered it to be superior.[29]

GE had hoped that its significant investment in neutral buoyancy would provide it an entrée into the Workshop project, but that was thwarted because a MSFC group grew organically out of the AAP program in 1965. As was true at Boeing, neutral buoyancy experiments at Marshall began with the individual initiative of scuba enthusiasts. Charles 'Charlie' Cooper, a twenty-eight-year-old electrical engineer in the MSFC Manufacturing Engineering Laboratory, recruited a colleague, Charles Stokes, to experiment in an 8-foot (2.4 m) water tank used for the explosive-forming of metal structures. The first problem was how easy it would be for astronauts to move around large, high-mass objects in microgravity, as the lack of weight did not alter their inertia. In an early Marshall conception for an AAP mission, an Apollo spacecraft would rendezvous with its empty S-IVB last stage and an astronaut would remove its large, spherical ST-124 inertial-guidance platform from the rocket. Cooper and Stokes took one of the spheres and filled it with water until it was neutrally buoyant and tried pushing it around in the tank. It proved easier than expected (Figure 4).[30]

Cooper's memory of when this impromptu experiment occurred is vague, but he believes it was soon after the first American EVA, which Edward White made from Gemini IV on 3 June 1965. (Two-and-a-half months earlier Alexei Leonov had taken the first ever 'spacewalk' from Voskhod 2.) He suggested that MSFC contact the Manned Spacecraft Center about what was learned from White's experience, but it was not done. A likely cause was the intense rivalry between Houston and Huntsville, which was exacerbated by Marshall's intrusion on MSC's sacred astronaut turf for AAP projects like the Workshop. As a result, Huntsville often tried to keep secret from Houston what it was doing to prevent a turf battle or an order from NASA Headquarters to stop.[31]

When Cooper and Stokes' boss, Robert Schwinghammer, found out about the experiments, he chewed them out for unauthorized action, then supported the idea. He sent Cooper and Stokes for training in the Navy's pressure suit

Figure 4. A diver, likely Charlie Cooper, holding a S-IVB propellant utilization valve at NASA Marshall Space Flight Center's 8-foot explosive-forming tank, November 1965.
Courtesy of NASA MSFC.

school in Miramar, California, and (to continue the almost exact parallel with ERA's experience) borrowed two Mark IV Arrowhead spacesuits from it. They began to accumulate experience in the 8-foot tank on how to work in neutral buoyancy with air-pressurized suits.[32]

In the winter of 1965/66, Schwinghammer's group repurposed a larger 25-foot (7.6 m)-diameter explosive-forming tank that, like the other, was sunk in the ground. They turned an unneeded, corrugated-metal prototype interstage section from a Saturn V into the cylindrical walls of a shed, put a conical, tent-like roof over it, and installed lights and steam-heating for the water. On 10 January 1966, Werner Kuers, Director of the Manufacturing Engineering Laboratory, reported to Marshall Director Wernher von Braun in the Weekly Notes that the facility was ready. It was apparently the first time von Braun heard of it. Work in pressure suits, Kuers noted, would soon begin on '[a]ir lock ingress, egress, operation and familiarization . . . with a simplified air lock mock-up' for the Workshop, as well as '[r]emoval of the S-IVB hatch cover' on the dome of the liquid-hydrogen tank that would form the living quarters and experiment area. Later they would work on studies of the removal of the ST-124 platform sphere and a 'propellant utilization valve' from the stage's J-2 engine, another projected early task. 'Two of our people [presumably Cooper and Stokes] have been checked out in astronaut suits so far,' and more would follow. But it took six months to make the large tank into an operational facility. Kuers reported on 25 July 1966 that '[f]or the first time last week, the Mark IV pressure suit was used under water in a neutral buoyancy zero g simulation experiment' in the large tank.[33]

ERA and the Gemini EVA crisis, 1966

The rise of Marshall's Orbital Workshop in 1965/66 eclipsed Langley's Manned Orbiting Research Laboratory as NASA's most likely interim space station. That may be the reason why Environmental Research Associates' contract with Langley appeared to be about to run out. Sam Mattingly's attempts to advertise his little company's expertise through presentations of films and data to various audiences at NASA had fallen on deaf ears. In the case of MSFC, it is now apparent that as it developed its own capability rather secretively, it never considered seeking ERA's help. As for MSC, until June 1966, the attitude of key personnel in Houston was dismissive, in Mattingly's view. They thought it was too much trouble and they just did not need it. Kenneth Kleinknecht, the deputy manager of the Gemini program, said in 1998 that some (presumably in the Astronaut Office) viewed underwater training as 'below the dignity of the astronaut.'[34]

The May 4 training plan for Gemini X through XII, the last three missions, confirmed that that EVA training would be carried out on the air-bearing surface, in the zero-G airplane, and in the vacuum chamber to practice the depressurization and pressurization procedures for the spacecraft, which had no airlock. White's EVA the previous year had gone very well, except that compressing his rigid suit enough to get down and close the hatch over his head proved very difficult. But he had done no meaningful work in space, other than testing a handheld maneuvering unit that quickly ran out of compressed oxygen. Nor was anything known at the time, due to Soviet secrecy, of the serious crisis Alexei Leonov experienced in March 1965, trying to re-enter and turn around in the Voskhod's inflatable airlock. Leonov had to bleed down his suit pressure, risking the bends, in order to make this spacesuit flexible enough to get back in and was completely exhausted by the effort. But to all appearances, his experience was as euphoric as White's. And no one had ventured out since, because David Scott's planned spacewalk on Gemini VIII in March 1966 never happened due to an emergency return to Earth.[35]

Everything was to change after Eugene Cernan's near-fatal Gemini IX experience on 5 June 1966. He had an ambitious plan to go to the back of the spacecraft, don an Astronaut Maneuvering Unit (AMU) developed by the Air Force and then fly free, using its rocket thrusters to test maneuverability. Because of the hot jets, his suit had extra layers of insulation that made it even stiffer. But he quickly became seriously overheated by the enormous effort it took to fight the suit and get himself into position. Lacking adequate handholds and footholds, Newton's third law of motion quickly made itself apparent. Every action, whether it was to turn a valve, or deploy the arms of the AMU, produced an equal and opposition reaction – his body would go the other way. He quickly overtaxed the cooling capacity of the Gemini suit, which relied on the recirculation of the oxygen around his body and head. His visor fogged over and sweat ran into his eyes, with no way for him to do anything about it. His commander, Thomas Stafford, agreed that he had to get back in. That again proved enormously difficult, especially as Cernan was approaching the limit of his endurance. If he had become incapacitated, Stafford would have to throw him overboard in order to close the hatch and make it possible to get back to Earth. When they had finally succeeded in repressurizing and Cernan opened his faceplate, he was so overheated that he looked red as a boiled lobster. While some in Houston, including astronaut colleagues, felt that Cernan had just botched the EVA, many began to grasp that doing useful work outside might be a lot harder than anticipated. Apparently EVA was not well understood after all.[36]

Ten days after Cernan's walk, on 15 June, Mattingly and Loats staged a pre-planned demonstration for a dozen representatives from NASA and IBM, an attempt to scare up new business as the Langley contract was about to end. Knowing that removing the S-IVB dome hatch and attaching a flexible boot from the airlock to the opening was a critical task for the Workshop, ERA had built a mockup of the area based on pictures in a trade magazine. There were seventy-two bolts holding the hatch cover to the propellant tank, and the divers demonstrated how difficult it was to remove them. The four Marshall representatives, including Charlie Cooper, however dismissed the test as inaccurate, according to Mattingly. 'You don't know what the hell you're doing' is his summary of their reaction. But fortunately for ERA, Don Jacobs of MSC, motivated by Cernan's near-disaster, saw their experience as more useful and arranged to transfer funding to Langley for an extension on their contract. Their first job would be tasks scheduled for Michael Collins's EVAs on Gemini X in late July, notably attaching the hose of a handheld-maneuvering gun to a connector on the spacecraft exterior that would supply nitrogen gas. Jacobs quickly shipped a mockup of parts of the Gemini spacecraft to Baltimore.[37]

Thus began by far the most intense period of ERA's neutral buoyancy experiments. The summer 1966 school break allowed the company to take the pool for longer periods of time. On 30 June-1 July, with the mockup and Arrowhead suits, the ERA divers simulated the Gemini X hose attachment, which 'showed that the task was doable but would require three hands to complete without incident' (Mattingly). The results and films were passed along to the crew, John Young and Michael Collins, but, pressed for time to prepare for their launch on 18 July, they dismissed this information as obvious.[38]

Jacobs, however, immediately delivered a more elaborate mockup of the adapter section of the Gemini spacecraft, with AMU, to evaluate the Gemini IX EVA. Cernan visited on the 11th, the first astronaut to appear at the McDonogh pool. Then or on the next visit, he was indoctrinated in the critical safety procedures that the company had developed. Mattingly and Loats insisted that everyone, including astronauts, who suddenly began appearing with some regularity, watch a demonstration by a suited diver before they did anything. Mattingly told them: "This is what we expect you to do. If you're going to do something else, you'd better advise us in advance, because if we don't like it, we're going to haul you out of the pool.' And they believed me, and we would have, too, because we were a little tense at the time.'[39]

On 28–29 July, Cernan returned to do a simulation of the AMU-donning task in his own Gemini G4C spacesuit, observing on day one and doing it himself four times on day two. Mattingly noted a distinct change in his behavior before and after the exercise:

> [A]t least half of NASA thought that Cernan had screwed up because he was a poor astronaut, and Cernan knew that. So when he came in, he was as tight as a drum, and it was obvious to us, because we thought so too. So he watched – I think it was Bruce [Tharp] in the water, and he was very attentive, and when he got out of the water, it was like an entirely different person. His attitude, his personality, everything changed suddenly.
>
> Harry [Loats] and I had him up in the stands, and we said, 'First question we've got to ask you, how does this compare with orbit?'
>
> And he said, 'It's at least 75 percent accurate.' I loved it.

Cernan flew back to Houston and immediately reported the results, which were noted in a 1 August memorandum.[40]

A week earlier, MSC Director Robert Gilruth had already made the watershed decision for his center, however. On 25 July he wrote to Deke Slayton, head of the Flight Crew Operations Division:

> I have given a great deal of thought recently to the subject of how best to simulate and train for extra-vehicular activities and have reached the conclusion that both zero 'g' trajectories in the KC-135 and underwater simulations should have a definite place in our training programs.

The aircraft was better suited for rapid movements, while the neutral buoyancy was 'far better for the study of positioning, hand holds, and the initiation and termination of all movements between points.' He directed Slayton to send astronauts to ERA, probably including the three spacewalkers White, Cernan and Collins, 'to get a better evaluation of the techniques involved' and to do some evaluations for the EVAs scheduled for Gemini XI and XII. Gilruth, moreover, directed that Flight Crew Support Division (responsible for training) 'should proceed immediately to develop an underwater simulator. I have some specific ideas on how this is to be done. . ..'[41]

What shaped Gilruth's decision? He clearly had talked to people who had been to Baltimore. Moreover, Gemini X had splashed down four days prior to the memo, and Collins had had some difficulties with controlling his body positioning and completing his tasks, if not as severe as Cernan's, because his objectives were simpler. We also know that General Electric had recently briefed Gilruth and 'associates' about their neutral buoyancy work. With no knowledge of the MSC Director's decision, on the 29th, A. W. Robinson of GE wrote thanking him for listening to the briefing and offering the company's facilities and services to train the Gemini XI and XII astronauts. Gilruth politely turned him down several weeks later, as the astronauts had little time and MSC had already committed to ERA. One can presume that the Director had previously talked to his staff about the tradeoffs between air- and water-pressurized spacesuits, and had chosen the former because it was a superior simulation of spaceflight conditions, but there is no evidence. In any case, MSC already had a convenient contract arrangement with ERA and was getting good results. Gilruth did promise that Mercury astronaut Scott Carpenter, who would be advising him on the creation of a Houston tank and who had already been in 'direct correspondence' with GE, would visit its facilities 'in the latter part of September.'[42]

As an astronaut, Carpenter was in an unusual position. Although world-famous as one of the Mercury Seven, he was controversial at MSC because of what many thought were serious mistakes during his May 1962 three-orbit Mercury flight. He probably never would have gotten another spaceflight, but injuries sustained in a 1964 motorbike crash then ruled him out of flight status anyway. A Navy officer and highly experienced scuba diver, Carpenter had taken two leaves of absence to devote himself to undersea exploration during his service's Sealab and Sealab II missions. Back in Houston from living a month underwater in late 1965, he became an Executive Assistant to Gilruth. He was thus a natural choice to advise the latter on the implementation of neutral buoyancy training after Gilruth's decision. Surveying all companies doing such work seems to have been part of Carpenter's job. In addition to being at GE, he apparently had come directly from Convair/General Dynamics when he arrived in Baltimore in mid-October.[43]

Meanwhile, on 10 August ERA divers in the McDonogh pool, wearing recently supplied Gemini G2C suits, carried out simulations of the EVA tasks assigned to Richard Gordon on Gemini XI, scheduled for mid-September. The Gemini program's hectic pace prevented Gordon from taking part, however, as was the case for Collins. NASA was in a rush to complete Gemini before the end of the year, so that it could move on to Apollo and the looming, end-of-the-decade Moon-landing goal. Films and information were again sent to the crew, but it did not help, because Gordon had no secure handholds or footholds in his primary task, attaching a tether between the Agena docking vehicle and the Gemini spacecraft. He became overheated and exhausted, forcing an early end before any ERA recommendations for revised procedures could be carried out. It was an experience almost as worrying as Cernan's.[44]

Fortunately there was enough time to train Buzz Aldrin for Gemini XII, with a planned launch in mid-November. According to Sam Mattingly, the Gemini program manager, Charles Mathews, had to intervene with Gilruth to get Aldrin sent to Baltimore over the resistance of the Astronaut Office. Such training seemed urgent, as Aldrin was to repeat the experiment to fly the Air Force's Astronaut Maneuvering Unit. Handholds, footholds and procedures were improved over Gemini IX. ERA carried out its first simulation on 23 August and Aldrin appeared on 12 September, Gemini XI's launch day. Training was interrupted so he could watch the liftoff on a pool-side TV. Apparently all did not go perfectly with the exercise, as two days later ERA personnel tested some further revisions to procedures. But it was all for naught, as NASA's leadership decided in late September to cancel the AMU as too problematic, especially in view of Richard Gordon's recent difficulties. With only one Gemini mission left, it seemed politically and programmatically more important to prove that NASA had EVA in hand than it was to make the Air Force happy (Figure 5).[45]

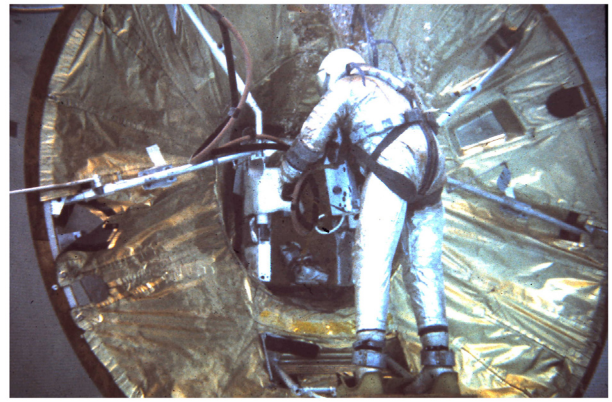

Figure 5. Buzz Aldrin training for Gemini XII in the McDonogh pool, fall 1966. Courtesy of Sam Mattingly.

Aldrin was angry about losing the AMU, as the ERA men found out at the next training sessions on 16–17 October. Instead, he was given a task board with various exercises like turning a screw with a power tool, opening and closing Velcro patches, and so forth. While training in the pool one day with Cernan, his backup for Gemini XII,

> I let out a high-pitched staccato screech. When a startled Gene Cernan looked up and asked what was wrong, I glared at him and said, 'Shut up and pass me a banana.' The joke spread and whenever I was back in Houston, parties unknown to me kept a supply of bananas in my office.

Aldrin felt that the tasks were so simplified that the monkey he gave his wife could do it. But he was very focused on mastering them and he was a natural in the water, according to Bruce Tharp.[46]

Aldrin returned on 29 October to run a full simulation with his commander, James Lovell, who stayed out of the pool but communicated with him via radio as they followed the flight plan. The head of the human space program at Headquarters, George Mueller, observed from a diving board. When Gemini XII flew in November, Aldrin completed all EVA tasks as planned. He demonstrated that the new, slow, deliberate manner of walking in space, with ample tethers, handrails, handholds and footholds, and procedures practiced underwater, had defeated the zero-G monster.[47]

Even as Gemini XII training intensified, Houston engaged both ERA and Marshall Space Flight Center in neutral buoyancy studies of the challenges presented by the Apollo Applications Program, especially the Orbital Workshop. No doubt as a direct result of Gilruth's 25 July order, Alan Bean, fresh off assignment as Gemini X backup commander and responsible for AAP in the Astronaut Office, went to Huntsville on 6–7 September. He spent two hours in the Marshall 25-foot tank in an Arrowhead suit evaluating Orbital Workshop activities. Among other things, he had removed 'bolts from a simulated S-IVB hatch cover.' The MSFC staff were very excited by Bean's knowledge and attentiveness to detail. In his Weekly Note to von Braun, Werner Kuers stated:

> Lt. Commander Bean was quite enthusiastic and outspoken about neutral buoyancy as one of the mandatory methods of simulations for all the S-IVB Workshop experiments. In addition, he apparently had been told of our plans regarding the new large neutral buoyancy type simulator, and in response to his point blank questions regarding this, he was candidly shown the design blueprints by responsible ME [Manufacturing Engineering] personnel. Consequently, Houston is now aware. [Underlining in original]

This the first mention discovered so far of Marshall's plan for a permanent facility, one that would be finished two years later.[48]

Bean subsequently visited ERA in Maryland in mid-November to see the Workshop simulations going on there. Houston had given ERA a second contract, finalized on 30 September, to evaluate the Orbital Workshop airlock and dome hatch-cover problem. Work on that began on 4 October, and Mercury astronaut Scott Carpenter arrived on the twelfth. After he watched Bruce Tharp take off three bolts in thirty minutes, according to Sam Mattingly, Carpenter was only able to get one out or partly out, because he lacked the experience that the seasoned ERA diver had. The Mercury astronaut wrote shortly afterward: 'Trying to loosen 72 bolts floating underwater and wearing a weighted, pressurized space suit turns out to be a nearly impossible job. I was surprised to find I had as much difficulty doing such simple tasks as other astronauts had during their space walks.' The preliminary conclusion from the ERA study was that it would take two astronauts six hours to get all the bolts off, if they used a power tool and a right-angle drive, but even that estimate seems optimistic.[49]

The demonstration of how difficult that task was in a pressure suit in simulated weightlessness had an immediate effect on Huntsville's design. At a 14 October meeting there between representatives of MSFC and MSC, 'agreement was reached . . . regarding the evaluation of the three proposed designs for a quick-opening hatch for the S-IVB hydrogen tank.' The meeting came about because Houston had already ordered airlock mockups for neutral buoyancy training from contractor McDonnell Aircraft and was about to order another from Marshall for its own tank. Whether Carpenter visited Huntsville is unknown, but seems likely. A little over a year later, von Braun gave him the primary credit for raising NASA's consciousness about neutral buoyancy.[50]

Consolidating the neutral buoyancy technological system at NASA

The intense and exciting days at the McDonogh School in fall 1966, which required significant concessions by the headmaster, were destined to come to an end. To keep the operation going and to complete what Sam Mattingly saw as the capstone demonstration of neutral buoyancy's value, he sold Houston on a final evaluation of Gemini XII. As an addition to the airlock contract, Aldrin returned to Baltimore on 2 December to run through all his recent orbital activities in order to make systematic comparisons. He confirmed that neutral buoyancy provided a close facsimile of many aspects of actual EVA. But with Langley no longer providing money, Gemini over, Houston building its own tank, and Huntsville already operating a provisional system, ERA's days as a training facility for astronauts appeared to be numbered. Although it did get a loan of an early Apollo development suit, the only contracts it received for neutral buoyancy thereafter were for advice and assistance to MSC in building its facility in 1967. The Apollo fire at the end of January 1967, which killed three astronauts (including Edward White) in a launch-pad test, was another blow. New stringent safety regulations, which Mattingly thought were unnecessary, required that ERA maintain a decompression chamber and medical help on-call in case of a diving accident. The company had to find another pool to work in and bought a chamber at government expense, but never used it and did little new neutral buoyancy work. ERA carried out small experimental contracts for NASA and other government agencies until the early seventies, when Sam Mattingly and Harry Loats decided to end the partnership and seek other jobs.[51]

As for the Houston facility, it proved harder to start up than originally anticipated. 'It's just a tank of water' was the dismissive or ironic summary of neutral buoyancy that Mattingly ran into at the time. Its complexity was easy to underestimate. Immediately after Gilruth's order, MSC officials expected its facility could put it in operation by the end of 1966.[52] That was thought feasible because it only involved moving the former water egress training tank at Ellington Air Force Base to Building 5 at MSC and equipping it for underwater work. But external viewing ports were added, as was a decompression chamber on the shelf at the edge of the tank, a ladder, a hoist, lighting, heating and so forth. Trained scuba personnel were critical. As of 13 February 1967, there were only two available, although six were required for operations. The Astronaut Office also decided that all astronauts needed scuba training as well, if not already expert. As a result of all the necessary changes and training, the tank, first called the Water Immersion Facility (WIF), only came into operation in June, and after more fixes, was approved for regular operation on 1 August by a board that included Scott Carpenter. Much of its work concerned Apollo training for lunar missions, but it included some AAP tasks.[53]

Meanwhile, Huntsville was already working in its two metal-forming tanks, but the very large Neutral Buoyancy Simulator (NBS) took two more years to build. Apparently plans went back to the beginning of 1966, when the 25-foot tank was being refitted, but a year later Werner Kuers complained that no progress had been made on the NBS. Eventually Wernher von Braun found the money to construct it as a 'tool' – effectively hiding it from Headquarters – because calling it a 'facility' would mean it would have to go through a centralized process that could take years (Figure 6). At 75 ft (23 m) in diameter and 40 ft (12 m) deep, this huge, cylindrical tank could hold mockups of the full diameter of the S-IVB Workshop. One unique aspect of the NBS was a 'safe haven' chamber at the bottom, to which spacesuited trainees could retreat in case of suit failures during extended underwater sessions, rather than risking decompression sickness during emergency ascents from depths greater than 33 ft (10 m). Completed by the end

Figure 6. Wernher von Braun in a Mark IV Arrowhead spacesuit, just before entering the interim 25-foot tank at NASA Marshall, November 1967. Courtesy of NASA MSFC.

of 1968 and revealed to the public in early 1969, the NBS provoked government investigators to threaten Marshall managers with jail, although von Braun's center eventually got away with a paper reprimand. It proved critical to completing the design work and training for, and inflight repair of, the Skylab station launched in 1973.[54]

As NASA consolidated its training at the two facilities, the aerospace crash of the late sixties and early seventies killed off the remaining corporate neutral buoyancy work. Boeing had already mothballed its facility in 1967. As for Convair/General Dynamics and Garrett AiResearch, there is no sign they operated after the sixties. At General Electric, the cancelation of Manned Orbiting Laboratory in June 1969 was the deathblow for its underwater work in the Philadelphia area and the Virgins Islands. The Nixon Administration decided that unmanned reconnaissance satellites were a better investment, killing the last exclusively military human space program. Soon thereafter President Nixon (with full collaboration by a Congress controlled by Democrats) curtailed the Saturn/Apollo program, ended all plans for space stations after Skylab, squashed talk of Moon bases and Mars expeditions, and limited the NASA human program to a Space Shuttle, shared with the military, that could not fly before the late seventies (actually 1981). That both the Huntsville and Houston neutral buoyancy facilities survived the lean seventies can only have been because they were relatively cheap, and Huntsville's large tank had unique value for the Shuttle program, like training to work with the Hubble Space Telescope. But Charlie Cooper retains a certain bitterness at what he claims were multiple attempts by Johnson (as it was called after 1973) to kill Marshall's facility off. It finally happened when the gigantic Neutral Buoyancy Laboratory opened in 1997.[55]

This historic rivalry and size differences aside, the two centers had effectively co-invented the neutral buoyancy technological system, as the corporate activity had so little legacy. Both used gas- (as opposed to water-) pressurized suits, scuba-equipped safety divers, specially modified film equipment, and heated and well-lit water tanks with filtering systems to retain clarity. Similar, well-entrenched safety cultures were needed to protect the astronauts and divers from danger. Both arose as local initiatives from below, Houston's from Trout, Mattingly and Loats' work at Langley and ERA, and Huntsville's from the scuba experiments of Cooper and Stokes. Indeed, it is striking how much scuba diving, a hobby that mushroomed in the 1950s after Cousteau and Gagnan invented the Aqualung, was an enabling technology for neutral buoyancy. The low technological barriers to entry – a little scuba experience (which Mattingly and Loats hired by going to the local dive shop), access to full-pressure suits, swimming pools or tanks, and simple mockups that could be built in-house – meant that it was possible for a small government division, or a small company like Environmental Research Associates, to compete with giant aerospace corporations in the development of neutral buoyancy. That this training method was unanticipated or dismissed as unnecessary also favored innovative, small groups empirically assembling a system from below, rather than a large organization ordering development from above.

Neutral buoyancy was also clearly contingent in its origin, as individual initiative and luck had much to do with why the two NASA groups succeeded where others reached a dead-end. If ERA's last-ditch demonstration had not taken place ten days after Cernan's nearly disastrous EVA, and the company had gone out of business in 1966, Houston might have had to seek expertise elsewhere, with unknown effects on training for the last Gemini missions. And given the turf battle between Houston and Huntsville, and the quasi-legal way Marshall funded the NBS, it was always possible that Headquarters would have nipped Huntsville's independent group in the bud. Perhaps one of the corporations would have found a sustainable NASA contract in their place. Such speculation quickly runs aground, but it serves to demonstrate that *the way* the neutral buoyancy technological system was assembled was 'socially constructed' and far from inevitable. However, the ultimate convergence on nearly identical technological characteristics all over the world, based on NASA's example, indicates that there probably is one superior technological solution for simulating on Earth the characteristics of extended spacewalking – *the how* was not, at least in gross terms, socially constructed, but grounded rather in physical reality. We are arguing here for what some have called 'soft' social constructionism.[56] Thus, the story of how neutral buoyancy training was invented, or assembled, is instructive, not only for space historians and practitioners, but also for historians of technology.

References

1. Shayler DJ. *Walking in Space*. Chichester, UK: Springer-Praxis; 2004:130–140. . *NASA/JSC NBL website*. http://dx12.jsc.nasa.gov/site/index.shtml; Accessed 5.01.15. Messerschmid E, Haigneré J-P, Damian K, Damann V The European Astronaut Centre prepares for International Space Station operations. *Acta Astronaut.* 2004;54:527–539. esp. 533–534. . *Japanese Aerospace Exploration Agency (JAXA)*. Weightless environment test building website. http://iss.jaxa.jp/ssip/ssip_wet_e.html; Accessed 5.01.15. Morring Jr F. Astronaut training: China's cadre of astronauts is slowly mastering the basics. *Aviation Week Space Technology.* 2009;171(October (14)):48–49.
2. See some of Thomas P. Hughes's many works: *Networks of Power*. Baltimore: Johns Hopkins University Press; 1983. The evolution of large technological systems. In: Bijker W, Hughes TP, Pinch TJ, eds. *The Social Construction of Technological Systems*. Cambridge, MA: MIT Press; 1987:50–82. *Rescuing Prometheus*. New York: Pantheon; 1998.
3. Hacker BC, Grimwood JM. *On the Shoulders of Titans: A History of Project Gemini*. Washington, DC: NASA; 1977:372. Compton WD, Benson CD. *Living and Working in Space: A History of Skylab*. Washington, DC: NASA; 1983:170. Hansen JR. *Spaceflight Revolution: NASA Langley Research Center From Sputnik to Apollo*. Washington, DC: NASA; 1995:303. Aldrin Jr EE 'Buzz', Warga W. *Return to Earth*. New York: Random House; 1973 :173–175. Cernan E, Davis D. *The Last Man on the Moon*. New York: St. Martin's; 1999 :156. Collins M. *Carrying the Fire: An Astronaut's Journeys*. New York: Farrar, Straus and Giroux; 1974:192–193. Shayler DJ. *Walking in Space*. 35:131–132. Of the astronaut memoirs, only Aldrin's gets the details right, and mentions the two ERA partners and their company, if none of them by name.
4. Mattingly GS, Charles JB. A personal history of underwater neutral buoyancy simulation. *The Space Review*, 4 February 2013. http://www.thespacereview.com/article/2231/1; Accessed 3.12.14. *Neutral Buoyancy as a Training Aid*. http://en.wikipedia.org/wiki/Neutral_buoyancy_simulation_as_a_training_aid (originally written by Mattingly and Charles), Accessed 3.12.14. Jones TD. *Gemini: Blazing a Trail to the Moon*. Aerospace America (October 2012), 16–19, here 18–19. The 24 Sept. 2011. "Gemini XLV" symposium at the Glenn L. Martin Aviation Museum in Middle River, Maryland, in which Mattingly made a presentation, was the impetus for the Jones article and gave Michael Neufeld his first acquaintance with the ERA story.
5. Compton, Benson. *Living and Working in Space*, 170. Dunar A, Waring S *Power to Explore: A History of Marshall Space Flight Center, 1960–1990*. Washington, DC: NASA; 1999:187–188. Neufeld MJ. *Von Braun: Dreamer of Space, Engineer of War*. New York: Alfred A. Knopf; 2007:421. . The only source that discusses neutral buoyancy's MSFC origins is a popular article: Hickam Jr HH. Charlie and the Aquanauts: how a team of NASA employees made Huntsville, Alabama, the best place to learn about life without gravity. *Air Space Smithson*. 1993;(June/July):46–53.
6. Mackowski MP. *Testing the Limits: Aviation Medicine and the Origins of Manned Space Flight*. College Station, TX: Texas A&M University Press; 2006
7. Graveline DE, Barnard GW. Physiologic effects of a hypodynamic environment: short-term studies. *Aerosp Med.* 1961;32(August):726–736. Graveline DE. Maintenance of cardiovascular adaptability during prolonged weightlessness. *Aerosp Med.* 1962;33(March):297–302. .
8. Slayton DK. *Gemini Extravehicular Activity Program: Mission Planning, Crew Procedures and Training*. National Archives at Fort Worth, TX (hereinafter NAFW); 1964 (30 January), RG 255, E.75, Box 383, file 2: Extravehicular Activity.
9. Ibid, Johnson HI. Extravehicular maneuvering about space vehicles. In: *Gemini Summary Conference*, NASA SP-138. Washington, DC: Government Printing Office; 1967:91–106, here 98–100.. North W, Chief, Flight Crew Support Division, to Chief, Engineering Division, 17 Sept. 1965, and Johnson HI, Head FCSD Advance Planning Office, to Head, Planning and Scheduling Office, 22 Sept. 1965, both in NAFW, RG 255, E.154W, Box 2, CF Sep. 1965, and North to Chief, Engineering Division, 7 Jan. 1966, in Box 3, CF Jan. 1966. Collins M, who did EVAs on Gemini X, provides a good description of what the air-bearing trainer felt like in *Carrying the Fire*, 193–194.
10. Weightless tests at Wright-Patterson checkout life aboard Gemini spacecraft. *Space News Roundup* (NASA/MSC newsletter). 1964; 3(May (16)):1. Six astronauts get 'feel' of space in jet aircraft weightless flights. *Space News Roundup*. 1964; 3(September (23)):8. http://www.jsc.nasa.gov/history/roundups/roundups.htm; Accessed 23.01.15. Shayler. *Walking in Space*, 124–127, asserts that NASA had its own aircraft but this does not appear to be true.
11. Hansen. *Spaceflight Revolution* [chap. 9] ("Skipping 'The Next Logical Step'"), details the history of Langley's station studies.
12. Oral history interview (hereinafter OHI) of Mattingly GS by Neufeld MJ, 10 July 2014, Ocean Pines, MD, quote on p. 7. The date and name of the seal study is given in reference 1 to Environmental Research Associates. *A Study of the Performance of an Astronaut During Ingress and Egress Maneuvers Through Airlocks and Passageways*. 1964 (31 August), ERA 64-6, NASA technical report CR-66340 or N67-23328.
13. Hansen. *Spaceflight Revolution*, 299. Bruchey Jr WJ, Loats Jr HL, Mattingly GS. A technique of simulation of the operational and human factors design of the Apollo Airlock Module and the Gemini IX–XII Missions. In: *AIAA Paper 67-773, AIAA 4th Annual Meeting and Technical Display*, Anaheim, CA, 23–27 October 1967. Mattingly OHI, 7–9. Mattingly. *A Personal History*. No written documents relating to Trout's neutral buoyancy work appear to have survived in Langley records at National Archives Philadelphia, based on online finding aids and e-mail correspondence with an archivist there.
14. Mattingly SPACE card, 2 June 1964, in possession of the Mattingly family. Mattingly OHI, 7–9. Mattingly. *A Personal History*.
15. Mattingly OHI, 9–10. Mattingly. *A Personal History*.
16. Mattingly OHI, 8–10; quote on 8. Mattingly. *A Personal History*. ERA. *A Study of the Performance of an Astronaut*; 1964 (31 August).
17. Mattingly. *A Personal History*. Mattingly OHI, 10–11; photos, 7/18/64, in possession of the Mattingly family.
18. Mattingly. *Physical Examination For Flying* certificate, 1963–64, in possession of the Mattingly family. Mattingly OHI, 13–15. Mattingly. *A Personal History*. ERA. *A Study of the Performance of an Astronaut*.
19. Mattingly OHI, 16–19. Mick J, Morris E, Tharp B, OHI by Neufeld, MJ 11 July 2014, Ocean City, MD, 1–4. Trout Jr OF, Loats Jr HL, Mattingly GS. *A Water-Immersion Technique for the Study of Mobility of a Pressure-Suited Subject Under Balanced-Gravity Conditions*, NASA TN D-3054, January 1966; report dated 22.09.1965.
20. ERA. *A Study of the Performance of an Astronaut*. Trout, Loats, Mattingly. *A Water-Immersion Technique*. Bruchey, Loats, Mattingly. *A Technique of Simulation*, 1–6. Mattingly OHI, 9. Mick-Morris-Tharp OHI, 17–19.
21. Mattingly OHI, 11, 17–18. Mattingly. *A Personal History* ERA. *A Study of the Performance of an Astronaut*, 13 Trout, Loats, Mattingly. *A Water-Immersion Technique*, 5–6 Bruchey, Loats, Mattingly. *A Technique of Simulation*, 2–3.
22. Mattingly OHI, 18.
23. Mick-Morris-Tharp OHI, 10. Trout, Loats, Mattingly. *A Water-Immersion Technique*; 1965 (22 September), 4.
24. Murphy B. They simulated the weightlessness of space underwater, 1963. *Boeing News*. 29 August 1986, 5 (courtesy, John Lombardi, Boeing corporate archives) Dean RD, Langan RP, Erickson ER. *Airlock Assessment and Ergometric Evaluation Under Simulated Weightlessness (Neutral Buoyancy)*, Boeing Aerospace Group, report D2-90793-1, August 1965, NASA technical report N68-88626. "Weightless" (picture and caption), *Sandusky Register*, 19 December 1964, 3. "Underwater Space Research" (picture and caption), *San Antonio Express News*, 27 December 1964, 7.
25. Photo and brief caption, *General Dynamics Annual Report*, 1964, 13. First Test Series Underway in New Underwater Facility at San Diego, *General Dynamics News*, 20 September 1967, 3. Air and Water Pressure Space Suits Compared, *General Dynamics News*, 30 April 1969, 3, all in San Diego Air & Space Museum Library and Archives. Wortz EC, Browne LE, Schreck WH, Macek AJ, Robertson WG, Gafvert MR. *Study of Astronaut Capabilities to Perform Extravehicular Maintainence and Assembly Functions in Weightless Conditions*, NASA CR-859, September 1967, NASA technical report N67-36491. A second Garrett report is Wortz EC, Schreck W, Robertson W, Lamb G, Browne L. *A Study of Astronauts' Extravehicular Work Capabilities in Weightless Conditions*, NASA Contractor Report CR-1334, May 1969. It is described as a "final" report from a second Langley contract, and may have been written in 1968.
26. Marton T, Hunt SB, Klaus T, Cording CB. Neutral buoyancy submersion for the analysis of human performance in zero g. In: *AIAA Fourth Manned Spaceflight Meeting*, 13–15 October 1965, AIAA report no. 66A11626. Booda L. Man-in-the-Sea Projects Will Go Deeper, Stay Longer. *Undersea Technology*. 1965;6(March (3)):15–16, 18–19.
27. Day DA. All alone in the night: the manned orbiting laboratory emerges from the shadows. *The Space Review*, 23 June 2014, http://www.thespacereview.com/article/2539/1; Accessed 22.12.14. Photo in David HM. *Zero-G Slows Astronaut Performance*, Missiles & Rockets (8 November 1965), 34–37. The memoir of Bishop EJ. *Brooklyn, Buck Rogers and Me*. Lincoln, NE: iUniverse; 2003:40–41, mentions the Aquarama idea beginning after he began preparations to create the Buck Island facility discussed below. However, the timing does not seem right, as his activities there appear to be 1966 and later, and he may be referring to a later use of Aquarama than the first, which was before March 1965.
28. Bishop. *Brooklyn*, 22–67, 136–154, 161–170. Compton, Benson. *Living and Working in Space*, 20–27. Neufeld, *Von Braun*, 400–402. Bean to Slayton, 1 April 1967, in NAFW RG255, E.154H, Box 1, file 19-14 Apollo Trainers.
29. Trout Jr OF. Water immersion simulation of extravehicular activities by astronauts. *J Spacecraft Rockets.* 1967;4(June):806–808. . Bishop. *Brooklyn*, 24, 37–40. Air and water pressure space suits compared. *General Dynamics News*, 30 April 1969, San Diego: Air & Space Museum Library and Archives. Murphy. *They Simulated*. The latter article states that the Boeing group began with a water-pressurized suit. Pictures in the 1965 Boeing technical report Dean, Langan, Erickson. *Airlock Assessment*, do not appear to show water-pressurized suits, however.
30. Hickam. *Charlie and the Aquanauts*, 47–48.
31. Charles Cooper telephone interview by Michael Neufeld, 4 December 2014. Neufeld. *Von Braun*, 374:403–404.
32. Hickam. *Charlie and the Aquanauts*, 48–49. Cooper telephone interview, 4 December 2014.
33. Kuers Weekly Notes, 10 January and 25 July 1966, with von Braun marginalia, electronic copies courtesy Brian Odom, MSFC History Office. These are the first written documents found so far on neutral buoyancy at Marshall. The Office has some undated pictures of divers at the 8- and 25-ft. tanks in 1965.
34. Mattingly OHI, 12–13, 22, 26. Mattingly. *A Personal History* Kleinknecht KS. *OHI by Carole Butler*, 10 September 1998. http://www.jsc.nasa.gov/history/oral_histories/KleinknechtKS/KleinknechtKS_9-10-98.htm.
35. *Mission Training Plan* for Gemini X, XI and XII, 4 May 1966, NAFW, RG255. *Walking in Space*, 27–33. Siddiqi AA *Challenge to Apollo: The Soviet Union and the Space Race 1945–1974*. Washington, DC: NASA; 2000:455–456.
36. Cernan, Davis. *The Last Man on the Moon*, 129–145.
37. 15 June 1966 entries, ERA Visitor Register, 1962–72, in possession of the Mattingly family. Mattingly OHI, 22–25. Mattingly. *A Personal History*. Bruchey, Loats, Mattingly. *A Technique of Simulation*, 1.

38. Mattingly OHI, 27. Mattingly. *A Personal History* ("showed the task was doable"). Collins. *Carrying the Fire*, 192–93. Trout OF, Beasley GP, Jacobs DL. *Simulation of Gemini Extravehicular Tasks by Neutral-Buoyancy Techniques*, NASA Technical Note TN-D-5235, June 1969, NASA technical report N69-28024, 3, 5–8.
39. Mattingly OHI, 27 (quote). Cernan 11 July 1966 entry, ERA Visitor Register, 1962–72, in possession of the Mattingly family. Loats Jr HL, Mattingly GS, Hay GM. *Correlation Study of the Simulation of Gemini Extravehicular Activity with Flight Results*, NASA Contractor Report CR-1146, February 1969, 22. Trout, Beasley, Jacobs. *Simulation of Gemini Extravehicular Tasks*, 4, 8–10.
40. Mattingly OHI, 27. Loats, Mattingly, Hay. *Correlation Study*, 22–25. Trout, Beasley, Jacobs. *Simulation of Gemini Extravehicular Tasks*, 4, 8–10. Willman to Jones memo, 1 August 1966, NASA History Division, Historical Reference Collection folder 307.
41. Gilruth to Slayton, 25 July 1966, NAFW, RG255, E.154H, Box 3, file 19-1 Gemini Trainers.
42. Robinson, GE Missile and Space Division, to Gilruth, 29 July, and reply (drafted by Harold Johnson), 24 August 1966, in NAFW, RG255, E.154W, Box 5, file CF August 1966. Collins. *Carrying the Fire*, 228–239.
43. Cernan, Davis. *The Last Man on the Moon*, 51–52. Carpenter S, Stoever K *For Spacious Skies: the Uncommon Journey of a Mercury Astronaut*. Orlando, FL: Harcourt; 2002 :320–323. Career Astronaut Biographies: "Scott Carpenter, NASA Astronaut (Deceased)," http://www.jsc.nasa.gov/Bios/htmlbios/carpenter-ms.html; Accessed 30 December 2014. Carpenter 12 October 1966 entry, ERA Visitor Register, 1962–72, in possession of the Mattingly family. Mattingly OHI, 19–20.Mattingly *Wet Workshop Mockup: Response to JBC's questions*, 21 August 2012?, electronic document sent to John Charles, 2012.Mattingly remembered Carpenter as appearing without warning one day, so it is possible that he visited Baltimore once before the 12 October visit noted in the visitor register, which appears to cover only those who went to the office and not to the pool, and even then not consistently However, there is no evidence that Carpenter came earlier than 12 October, and Loats, Mattingly, Hay. *Correlation Study*, February 1969, 22, states that: "The Gemini IX simulation [i.e. Cernan] was the first instance of astronaut participation at ERA." Mattingly's memory that Carpenter arrived before Cernan is thus wrong. See the web articles "Neutral Buoyancy as a Training Aid" (originally written by Mattingly and Charles) and Mattingly. *A Personal History*, both cited in n. 4.
44. Trout, Beasley, Jacobs. *Simulation of Gemini Extravehicular Tasks*, 4, 10–16.
45. Mattingly OHI, 29. Mick, Tharp, Morris OHI, 16–17. Trout, Beasley, Jacobs. *Simulation of Gemini Extravehicular Tasks*, 4, 16–20. Mueller to Ferguson (Commander, USAF Systems Command), 30 September 1966, NAFW, RG255, E.75, Box 225, file 1. (Ferguson to Mueller, 12 July 1966, in Box 224, file 3).
46. Aldrin, Warga. *Return to Earth*, 172–75 (quote 174–75). Mattingly OHI, 29. Mick, Tharp, Morris OHI, 9–10, 16–17. Trout, Beasley, Jacobs. *Simulation of Gemini Extravehicular Tasks*, 4–5, 20–25. Gemini XII training reports, 17–23 October and 24–30 October 1966 in NAFW, RG255, E.154W, Box 5, file CF October 1966.
47. Aldrin, Warga, *Return to Earth*, 173, 181–83. Mattingly OHI, 29. Mick, Tharp, Morris OHI, 16–17. Trout, Beasley, Jacobs. *Simulation of Gemini Extravehicular Tasks*, 4–5.
48. Kuers Weekly Note, 12 September 1966, electronic copy courtesy MSFC History Office (quote). *A Chronology of the George C. Marshall Space Flight Center From January 1 through December 31 1966*. Huntsville: NASA MSFC, 1969, compiled by Jones LL, 73.
49. Carpenter MS. *Former Astronaut Scott Carpenter Helps Train Men as Aquanauts*, Deseret News (Salt Lake City), 8 November 1966 (quote). Bean 15 November 1966 entry, ERA Visitor Register, 1962–72, in possession of the Mattingly family. Jacobs (signed by Mitchell) to Kleinknecht. *Mid-Term Report, Contract NAS9-6584*, 19 October 1966, University of Houston Clear Lake Archives, JSC History Collection, Skylab, Box 516 Mattingly OHI, 19.
50. Kleinknecht to Ferguson (MSFC), 27 October (quote), and 25 October 1966; and Kleinknecht to Low, 23 September 1966, in University of Houston Clear Lake Archives, JSC History Collection, Skylab, Box 516. Wernher von Braun, "'Inner Space' Rehearsals for Outer Space Adventures!," Popular Science, February 1968, 106–108, 208.
51. Mathews (signed by Kleinknecht) to Chief, Gemini and Flight Support Procurement, *Amendment of Contract NAS9-6584*, 23 November 1966, NASM, RG 255, E.75, Box 244, file 7 (this is the only contract document surviving with an amount: $41,600). Mattingly OHI, 31–40. Mick, Tharp, Morris OHI, 26–29. Trout, Beasley, Jacobs. *Simulation of Gemini Extravehicular Tasks*, 5, 24–25. Loats Jr HL, Mattingly GS. *A Study of the Astronaut's Capabilities to Maintain Life Support Systems and Cabin Habitability in Weightless Conditions Mod 3: A New Technique for Investigating Cargo Transfer in Simulated Weightless Environments*, NASA CR-66708, November 1968.
52. Mattingly OHI, 31 (quote). North to Chief, Engineering Division, 29 July 1966, in NASM, RG255, E.154W, Box 5, CF Jul 1966, and North to Chief, Crew Systems Support Division, 16 August 1966 in same, CF August 1966.
53. Bilodeau to Johnson, 13 February 1967, in NAFW RG255, E.154W, Box 6, Official file 1967. Van Bockel to North et al., 13 February, Johnson to Slayton, 21 February, and Slayton to Gilruth et al., 24 February 1967, in NAFW RG255, E.154W, Box 7, CF February 1967; Zedekar to All Astronauts, 20 March 1967, in same, CF March 1967. Revised Project Approval Document, Neutral Buoyancy Simulator in Building No. 5, 2 May 1967, and Samfield et al. to Gilruth, 1 August 1967, both in NAFW, RG255, E.15, box 61.
54. Kuers Weekly Note, 30 January 1967, 5 August and 12 August 1968, Murphy Weekly Note, 3 February 1969, and Answer to Comment on Notes, 20 February 1967, electronic copies courtesy MSFC History Office. Hickam. *Charlie and the Aquanauts*, 49–52. Dunar, Waring. *Power to Explore*, 187–88.
55. Bishop. *Brooklyn*, 176–185. Day. *All Alone in the Night*. http://www.thespacereview.com/article/2539/1. Neufeld. *Von Braun* [chap. 18]. Cooper telephone interview, 4 December 2014.
56. See. Bijker, Hughes, Pinch. *The Social Construction of Technological Systems*.