MARSHALL SPACE FLIGHT CENTER,
NEUTRAL BUOYANCY SIMULATOR FACILITY
(Marshall Space Flight Center,
Building No. 4705)
Redstone Arsenal
Apollo Road
Huntsville Vicinity
Madison County
Alabama

HAER No. AL-129-B

HAER
ALA
45-HUVI.V,
7B-

BLACK & WHITE PHOTOGRAPHS

HISTORIC AMERICAN ENGINEERING RECORD
National Park Service
Department of the Interior
P.O. Box 37127
Washington, DC 20013-7127

ADDENDUM TO:
MARSHALL SPACE FLIGHT CENTER, NEUTRAL BUOYANCY SIMULATOR FACILITY
(Building No. 4705)
Redstone Arsenal
Rideout Road
Huntsville vicinity
Madison County
Alabama

HAER AL-129-B
ALA,45-HUVI.V,7B-

WRITTEN HISTORICAL AND DESCRIPTIVE DATA

REDUCED COPIES OF MEASURED DRAWINGS

FIELD RECORDS

HISTORIC AMERICAN ENGINEERING RECORD
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1849 C Street NW
Washington, DC 20240-0001

HISTORIC AMERICAN ENGINNERING RECORD

NEUTRAL BUOYANCY SIMULATOR (NBS) FACILITY

HAER No. AL-129-B

Location:	Building 4705, George C. Marshall Space Flight Center, Huntsville vicinity, Madison County, Alabama
Date of construction:	1968, 1979
Builder:	Marshall Space Flight Center
Present owner:	National Aeronautics and Space Administration
Present use:	Not in operation
Significance:	The Neutral Buoyancy Simulator (NBS) was NASA's first large, water-filled tank designed and built to create on Earth an experience very close to the weightless condition astronauts experienced when working in space. When properly weighted to compensate for their buoyancy, test engineers and astronauts in spacesuits were "neutrally buoyant," a condition closely simulating that of space. Various objects were buoyed or weighted to make them neutrally buoyant as well. The NBS was large enough to accommodate full-size mockups of space hardware and structures submerged within it. Results of tests in the NBS confirmed engineering designs and procedures, and astronauts initially practiced mission maneuvers there as well.
Historian:	Sara E. Wermiel
Project information:	Recording of the Neutral Buoyancy Simulator was completed during summer 2006 by the Historic American Engineering Record (HAER) for the NASA's George C. Marshall Space Flight Center. It was conducted under the general direction of Richard O'Connor, Acting Chief, HABS/HAER/HALS and Ralph Allen, Historic Preservation Officer, NASA MSFC. Thomas Behrens, HAER Architect, supervised the project. The recording team consisted of Laura Royer, Team Leader; Anne Harrington, Architect; Meghan Shannon, Architect; and Sara E. Wermiel, Historian. Photography was by Jet Lowe, HAER Photographer. Assisting the recording team were Paul Dumbacher, for review and comments on this report; Mike Wright, Marshall Space Flight Center Historian, for assistance locating materials and information about MSFC; and Ralph Allen, MSFC Historic Preservation Officer, for research materials, logistical support, and gracious hospitality.

Contents

1. Description

Completed in 1968, the Neutral Buoyancy Simulator (NBS) at the George C. Marshall Space Flight Center (MSFC) provided National Aeronautics and Space Administration (NASA) engineers and researchers with a means to develop, test, and refine hardware and maneuvers on Earth that would be used in the microgravity (often termed "weightless") environment of space. It also provided astronauts with an environment in which to practice operations outside the spacecraft called extravehicular activities (EVA).

Located in the southwest corner of a complex of metal buildings now collectively termed Building 4705,[1] the NBS consists of a large, steel water tank and its ancillary equipment, an adjacent control room, and various support facilities. The locations of service areas changed somewhat over the years of its existence, but in the last configuration the facility was housed in three main spaces: a large high-bay tank room, a control room east of the tank room, and a connecting office building between the tank and the control rooms. The main personnel entry is on the south side of the office portion of the building, where the name of the facility, "Neutral Buoyancy Simulator," is displayed over the door.

The tank room is essentially one high-bay area, measuring nearly 94' wide, 120' long, and roughly 40' high to its low-pitched, gable roof. It has a steel frame, corrugated siding, and no obstructing columns within the room. The floor is concrete. Approximately half of the south wall consists of a pair of doors that open so large objects can be brought inside. This building, which predated the NBS, was originally built to shelter mockups of Saturn I-Bs and was adapted for the NBS. Since it has few windows, and these only at ground level, one of the modifications was to put translucent panels in the roof to allow some natural light in.[2] Some roof panels can be removed to maneuver large test objects into and out of the tank. Three large, propeller-type exhaust fans mounted high in the north wall furnish ventilation when needed, and a north-south monorail hoist is suspended just east of the roof's peak and slightly off of the tank's centerline.

The tank is the principal feature of the NBS. Constructed of one-inch-thick steel plate and standing entirely above ground on a slightly raised concrete foundation that tapers smoothly to the

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[1] The various portions of Building 4705 were built at different times, and old documents may show individual numbers. The entire complex was assigned 4705 after all of the buildings were physically connected.
[2] The panels were put in 1968. "16 Receive Awards for Suggestions," *Marshall Star* 9 (Sept. 3, 1969): 2; "Building 4705," Karen Weitze et al., *Historic Structures Survey*, MSFC, 2003.

surrounding floor, it measures 75' in diameter, 40' deep, and it conservatively held 1.3 million gallons of water.[3] The tank is pierced at three levels with 71 observation portholes, 36 of which contained high-intensity lamps for illuminating the underwater area. Platforms circle the tank forming its second (15'-0½" above the floor), third (28'-4½" above the floor), and fourth, or top, (40'-11½" above the floor) levels. All levels are connected by stairs and elevators in the southwest and northeast corners of the building. Those in the northeast corner are actually within an enclosure outside the tank room. Also penetrating the tank about 8' above the floor is an airlock, sometimes referred to as the "dive bell," which divers could use to enter the tank at its bottom. Reached by a short, steel staircase, this airlock is a cylindrical chamber with doors that seal it from the tank and room. Entering the airlock, divers closed the outer door, admitted water from the tank until the pressure in the airlock balanced that in the tank (approximately 14 lb./in.^{2}), then opened the second door and entered the tank through it. Underwater video cameras (no longer extant) were attached to the wall of the tank where needed. The main floor of the tank room also holds a metal fabrication shop (northeast corner), water pumps and filters (northwest corner), controls for emergency air (west side), and the original visitor's entrance (southwest corner, adjacent to stairs and elevator). Exterior, metal, lean-to sheds connected to the room at ground level provided a covered chemical storage area on the north side and a mechanical room on the west side housing two air compressors for breathing air and a Nitrox gas-blending system. The southeast quadrant of the main floor did not have fixed equipment. Adjacent to the large south-wall doors, this area was available for test-specific support items.

At each tank platform level, extensions into the northeast and southwest corners of the room provide room for test equipment and support functions. All of these areas were directly served by one of the room's two elevators. The second level housed spacesuit maintenance in the northeast corner and a small maintenance and repair shop in the southwest corner. Spacesuit maintenance moved here from the ground floor of the adjacent office building at some point, presumably to locate this activity closer to where the suits were actually used. The maintenance shop supported both the NBS and various test missions.

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[3] Sources disagree on the capacity of the tank: figures range from 1.3 to 1.5 million gallons. Andrew Dunar and Stephen Waring, *Power to Explore*, 187, 648, give the capacity as 1.5 million gallons of water. The NASA webpage http://www.nasa.gov/centers/marshall/news/background/facts/nbs.htm, states 1.3 million gallons. And other publications, e.g. NASA News Release 69-4, 15 January 1969, gives 5300-cu-m (1.4-million- gal). "Workshop-ATM Tasks, Gear Are Studied Underwater," *Marshall Star* 9 (Jan. 15, 1969): 1-2.

Men's and women's locker rooms for test program participants are located on the third level, directly above the maintenance shop. When the Remote Manipulator Simulator was installed in 1980, its control room was built in the northeast corner of Level 3.

Level 4, surrounding the top of the tank, served as the entry and exit point for test personnel wearing spacesuits, and the life-support systems control room occupied the southwest corner. On the side of the tank directly in front of the control room were the two lifts that lowered and lifted suited individuals into and out of the tank. This control room contains a cylindrical hyperbaric chamber for the emergency treatment of rapid decompression victims.

The remainder of NBS management, control, and support facilities were last located in an office area east of the tank room. In this final configuration, a single-floor building contained locker rooms for the support divers, an instrumentation repair lab, a conference room, and offices for employees. Just east of the entrance lobby is the main control area, which includes a raised observation room, the control room, an audio/video recording room, and a shop for instrument maintenance. Externally, the tank room, office and entrance, and control area appear to occupy at least portions of three structures, but internally they are fully integrated. The office portion measures approximately 122' by 36', and the control area occupies an area about 51' by 59' in the eastern high-bay structure.

2. History

The Neutral Buoyancy Simulator was built to address a question that was entirely new in the history of humankind: what would it be like for human beings to do physical work outside of a spacecraft in the microgravity environment of space? During the 1960s, even as the lunar-landing programs consumed the bulk of NASA's time and budget, a group at MSFC was planning an Earth-orbiting laboratory in which astronauts would make extended stays. The orbiting laboratory that MSFC engineers envisioned finally came to fruition as Skylab, America's first space station, launched into orbit on 14 May 1973, but this configuration came about only after years of debate and competition between several basic concepts. Serious concepts for an orbiting American space station dated from Wernher von Braun's Project Horizon proposal to the newly created NASA in1959, and additional proposals from the Air Force and NASA followed over the next decade. Among the early options for creating the laboratory was one that called for launching components on several rockets, followed by astronauts who would assemble these components into the laboratory while on orbit. Whether for assembly of the station, or for maintenance and experimental work, all of these proposals involved astronauts spending significant amounts of time working outside the spacecraft. In NASA parlance, these were called "extravehicular activities," or simply "EVA."

But until June 1965, when Ed White left the confines of the Gemini 4 capsule, no American had been outside an orbiting spacecraft, let alone perform useful work. One of the NBS's creators recalled that engineers had some basic questions at the time about working in space:

> How well can an astronaut in zero-g[ravity] handle objects that have considerable mass and inertia, but no apparent weight? Such objects can readily be put into motion by the application of a small constant force, but cannot be quickly stopped. Can astronauts in bulky space suits safely maneuver large objects without the danger of being crushed by them? [4]

To answer these questions, MSFC engineer Charles Cooper believed they could simulate microgravity by using water to create "neutral buoyancy." Cooper was in a unique position to promote the idea. He was a scuba diver who understood how to control his buoyancy in water, and he was working on a team studying spacesuit designs and how well an astronaut might move around in them. The team's main piece of test equipment was a treadmill, but Cooper realized that a spacesuit would keep someone alive under water just like a diver's suit. If its tendency to float could be countered to make it neutrally buoyant, Cooper thought that the submerged environment just might resemble space reasonably well.[5]

"Neutral buoyancy" simply means a condition where people or objects in water neither sink to the bottom nor float to the surface. This is achieved by carefully adding weight to naturally buoyant objects, such as an astronaut wearing an inflated spacesuit, or by adding floats to counteract the weight of dense equipment that would otherwise sink. It was not a perfect solution, of course, but it proved to be a very good one nevertheless. Neither the test subject in a spacesuit nor the piece of equipment was actually weightless, but the net vertical force was very close to zero. And, unlike the vacuum environment of outer space, the water exerted some resistance to movement. But when

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[4] Joe Dabbs, "Neutral Buoyancy Simulator Has History of Invaluable Service to Marshall and the Nation's Space Program," *Marshall Star* 31 (Feb. 19, 1992): 2-3.
[5] Homer H. Hickam, Jr., "Charlie and the Aquanauts," *Air & Space* (Jun./Jul 1993): 47.

moving slowly, as an astronaut normally would during an EVA, this resistance was minimal. Thus, properly weighted or buoyed persons and objects in the water experienced something very close to the microgravity of space.

NASA engineers tend to be conservative and methodical in their approach to new challenges, taking one step at a time. In 1965, Cooper convinced co-worker Charles Stocks to help him try out the idea before they told anyone else about it. After normal working hours the two put a heavy, hollow ball (used as a mockup for a gyroscope) into a tank in their laboratory normally used to quench heated metal fabrications. The ball had a plugged hole, so Cooper removed the plug to let water in until the ball was neutrally buoyant. Cooper and Stocks quickly realized they could move the ball around easily. They felt the inertia due to its mass, but not its weight due to gravity, and the water offered little resistance to movement at slow speeds. After trying the experiment for himself, their boss, Bob Schwinghamer, enthusiastically supported expanding the tests to include people in spacesuits and a larger tank. MSFC Director Wernher von Braun agreed, and additional tests in a 15'-deep tank worked out most of the details needed to design and safely operate a functional facility.[6]

Obtaining the funds to build such a facility involved more than a little subterfuge, but "creative financing" was not new at Marshall (or, for that matter, at other NASA centers). The process by which MSFC built the NBS is reminiscent of the one it had used to construct its Redstone Missile Test Stand. Normally Congressional approval and funding had to be obtained to build any new "facility" at the center, but this was difficult and time-consuming to get. Additionally, NASA had assigned astronaut training to the new Manned Spacecraft Center near Houston, Texas, so any training facility would likely be built there, assuming something like the NBS was built at all. By the time the NBS was proposed, the Apollo Program was nearing its goal, and Congress had starting reducing NASA's funding. Programs such as an orbiting laboratory, then in the discussion stage, would have to use left-over Apollo components and facilities to control costs. Since nothing like the proposed NBS existed, even though something like it would be essential for the orbiting laboratory program, the MSFC managers played a bit of a game. MSFC could not build a "facility" without approval, but it could buy "tools." After being denied facilities money, Marshall managers reclassified the NBS components as tools, and built the facility using $1 million appropriated for Research and Development tools. Unable to hire contractors, MSFC staff personnel fabricated and

[6] Ibid, 48-51.

assembled the steel components themselves. A General Accounting Office audit ultimately led to a reprimand, but by that time the NBS was a valuable reality.

The tank was built quickly—according to one report, in only two months after materials had been delivered. In March 1968, the tank was complete, along with the hyperbaric chamber, dive bell, and breathing air system. Once the instrumentation and cabling were completed a little later that year, the NBS was ready for use. Some of the people who built it were transferred to operate it.[7]

By the end of 1968, tests were underway in the NBS. One of the men who tested the new facility early on was MSFC's director, Wernher von Braun, who had also gone into the previous tank wearing a spacesuit. In September he tried out the new tank, again wearing a spacesuit, examining the seals of the aft dome in an immersed mockup of a Saturn I workshop.[8] A NASA press release in January 1969 heralded the NBS program, saying that it "was providing information essential for design of the first U.S. space station. … Conclusions from the tests would be reflected in the Workshop's final design, with a decision expected in May 1969." [9]

When the NBS opened, the tests were developed by staff of the Propulsion and Vehicle Engineering Laboratory. Later, the NBS became an autonomous testing facility, handling tests ordered by MSFC and other NASA centers, private contractors, and academic researchers. The Manufacturing Engineering Laboratory originally managed the NBS, but with the many Marshall reorganizations over the years, the laboratory's location within the center changed, making it inconvenient for laboratory personnel to manage the NBS properly. In the 1990s, the facility was operated by the Systems Test Division of the Systems Analysis and Integration Laboratory.[10]

Like many NASA facilities, the NBS experienced changes over time. The most visible change greatly improved the facilities monitoring and control capabilities. For the first ten years of operations, NBS test control and monitoring equipment was crammed into a trailer standing just outside the east wall of the tank room.[11] As noted above, other controls were located in the tank room. In 1979, a permanent building was built in this space (where the trailer had sat) between the

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[7] David S. Akens, *An Illustration Chronology of the NASA Marshall Center and MSFC Programs, 1960-1973* MHR-10 (NASA MSFC, May 1974), 179; Hickam, "Charlie and the Aquanauts," 51; Andrew Dunar and Stephen Waring, *Power to Explore*, 187.
[8] David S. Akens, *An Illustration Chronology of the NASA Marshall Center and MSFC Programs, 1960-1973*, 191.
[9] Roland W. Newkirk et al., *Skylab; A Chronology* (http://history.nasa.gov/SP-4011/part2c.htm accessed Jan. 7, 2008).
[10] "Workshop-ATM Tasks, Gear Are Studied Underwater," *Marshall Star* 9 (Jan. 15, 1969): 2; 1990s, Paul Dumbacher, MSFC, former NBS Test Director, interview January 14, 2008.
[11] "The Neutral Buoyancy Simulator," http://www.nasa.gov/centers/marshall/news/background/facts/nbs.htm (accessed Dec. 3, 2007); Andrew Dunar and Stephen Waring, *Power to Explore*, 648; Charles Cooper, interview January 14, 2008; "NBS Gets New Control Room," *Marshall Star* 19 (Dec. 6, 1978): 3.

tank room and another high-bay building 36' further east. In this, the NBS's final configuration, this connecting, single-floor building contained locker rooms for the support divers, an instrumentation repair lab, a conference room, and offices for employees. When built, facilities for maintaining the spacesuits also occupied rooms in this area, but those rooms were unassigned in the later years of NBS operations. A new main entrance in the front (south) wall replaced the original pedestrian entrance at the southwest corner of the tank room.

This project also added a new control room with the latest in monitoring and control equipment, but the new control room would not fit within the new building. Instead, this room was built in the southwest corner of the eastern high-bay building. Inside, however, the new control room was accessed directly from the new lobby and was, thus, an integral part of the NBS area. The room, which featured a raised, computer room floor on two tiers, contained new equipment for monitoring the underwater tests. It had consoles for six participants, television monitors that provided fourteen views of the tank's interior, direct communications with test subjects, an audio/video taping facility, and data displays of test subject life support conditions. The underwater cameras could be remotely controlled from here, and the tests were taped for review after the test. A separate room behind the primary overhead displays housed the audio/video recording equipment, and a second room on the opposite (west) side provided space for invited visitors to observe the control room displays and activities through two large windows.

During the October-December 1978 construction period, the tank itself was drained and its interior sandblasted and painted. About 8 years later, the process was repeated. In July 1986, all of the hardware mockups in the tank were removed, the water was drained, and the interior was sandblasted and repainted once again. The NBS was back in operation in September.[12]

While primarily intended for the development of on-orbit hardware, tools, and EVA techniques, the NBS was also used for astronaut training, which was something of an unintended consequence. During the 1960s and early 1970s Apollo period, NASA's Manned Spacecraft Center near Houston, renamed the Lyndon B. Johnson Space Center (JSC) in 1973, had responsibility for the Apollo spacecraft and astronaut-related activities, like training, while MSFC developed launch vehicles like the Saturn V.[13] When Marshall was given responsibility for the orbital workshop, it built

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[12] "NBS Gets Face-lift," *Marshall Star* 19 (Nov. 8, 1978): 1; "NBS Now Stands Empty: Refurbishing Scheduled," *Marshall Star* 26 (July 23, 1986): 2.

[13] In this report, the center in Houston is called Manned Spacecraft Center (MSC) for time periods before 1973 and Johnson Space Center 1973 and after.

the NBS primarily for that project. But before long, astronauts were training in the tank, simply because it was by far the best such facility NASA had at the time. JSC had nothing like it.

The orbital workshop finally came to fruition as Skylab, and the NBS was the only neutral buoyancy facility in which a full-size mockup of it would fit. To support both hardware development and astronaut training, the roughly 30-person team remained in place throughout the Skylab program. They were organized in three sections: Pressure Suit Systems, Simulation Engineering, and Instrumentation and Control.

In January 1972, three different Skylab crews and backups were named, and they began intensive training, which included simulated EVA training in the NBS. Starting in February and continuing until a month before the planned May launch date, the first Skylab crewmen, Charles "Pete" Conrad, Jr., Joe Kerwin, and Paul Weitz, completed eighteen different training exercises in the NBS. Training of the second, third, and back-up crews for Skylab followed. Between 1969 and 1973, all Skylab astronauts trained in the NBS.[14]

On May 14, 1973, the Skylab 1 workshop was launched by a Saturn INT-21, the first two stages of a Saturn V, and Skylab 2, with the first crew, was scheduled to launch on a Saturn 1B the following day.[15] About a minute after Skylab 1 lifted off, a faulty latch allowed its micrometeroid and sun shield to tear off and, in the process, damage one of the craft's two primary solar array wings. The damaged solar wing eventually ripped completely off, while the second solar wing, which was folded for launch, became tangled in a metal strap that prevented its full deployment once on orbit. Although the workshop reached its intended orbit, with one primary solar wing gone and the other only partially deployed, it was woefully short of electrical power. Only the smaller solar arrays for the Apollo Telescope Mount had deployed properly. Without the shield to shade the workshop, its interior temperature soared. NASA personnel did not know exactly what had happened, except that the workshop was in trouble and either problem threatened to doom the whole project. Nevertheless, the decision was made to see if on-orbit repairs could be designed that might salvage the project.

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[14] "NASA Missions, Successes were Significant in '72," *Marshall Star* 13 (Jan. 10, 1973): 1; "Skylab Astronauts Here for Training," *Marshall Star* 13 (Jan. 24, 1973): 1; "Marshall NBS Training Prepares Skylab Astronauts for EVA's In Weightless Space," *Marshall Star* 13 (May 9, 1973): 2; "Skylab 4 Crew Concludes Neutral Buoyancy Training," *Marshall Star* 14 (Oct. 17, 1973): 1.

[15] Some sources refer to the launch of the unmanned workshop as Skylab 1 and the crew missions to it as Skylabs 2-4, while others refer to only the crew missions as Skylabs 1-3. The former convention is used here.

This was perhaps the finest hour for the NBS and its staff. Between the Skylab 1 launch and May 25, the rescheduled date of Skylab 2's launch, NASA and contractor personnel worked around the clock to find ways to save the damaged workshop. One team tackled the stuck solar array while a second focused on replacing the missing shield. The NBS and the Skylab mockup were used to test various procedures and tools that might free Skylab's solar wing. NBS workers quickly constructed a mockup of the damaged spacecraft in the NBS, working from images sent by Air Force satellites. With that and a mockup of the Apollo command module borrowed from JSC, NBS people and astronauts Russell "Rusty" Schweickart and Edward Gibson tested various tools and methods developed by MSFC engineers to free the solar array wing. Meanwhile, teams throughout NASA worked on ideas for shielding the workshop from the sun's heat. A temporary, parasol-type shade was developed that the first crew could deploy from through Skylab's airlock, but it would be too small to be a total fix. For that, MSFC proposed the solution that was adopted: a larger, rectangular shade made of aluminized fabric stretched between two poles. Astronauts would have to unfurl and deploy it on an EVA. To test the idea and deployment procedure, a mesh mockup—mesh to minimize water resistance during deployment—was built for the NBS.

While the Skylab 2 crew was doing its repair EVA, Charlie Cooper, Marshall's lead test engineer, and the person who first conceived the neutral-buoyancy concept for NASA, was suited up in the NBS, "ready to evaluate on-orbit procedures and to help modify them as needed in real time."[16] The procedures were a success. The Skylab 2 crew freed the solar wing. Developing the sun shade was more involved, and the MSFC staff remained highly engaged for the next six weeks. The Skylab 3 crew and backup deployed the twin-pole sunshade mockup several times in the NBS before flying and successfully deploying the real thing early in their July-September flight.[17] The third crew, Skylab 4, also trained in the NBS during August prior to their November 1973 launch. They remained in orbit for 60 days, completing the Skylab missions. After they ended in 1974, NASA and MSFC underwent a reorganization and the agency's budgets were significantly cut. By 1976 the NBS staff had dropped considerably.[18]

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[16] Joe Dabbs, "Neutral Buoyancy Simulator Has History of Invaluable Service to Marshall and the Nation's Space Program," *Marshall Star* 31 (Feb. 19, 1992): 3.

[17] "SL-3 Deployment Training in Marshall NBS Planned," *Marshall Star* 13 (June 20, 1973): 1; Hickam, "Charlie and the Acquanauts," 52; Andrew Dunar and Stephen Waring, *Power to Explore*, 205-10; "Skylab Rescue: Improvisation vs. a Race with Time," *Marshall Star* 28(May 11, 1988): 5.

[18] Charles Cooper, interview January 14, 2008; "Astronauts To Begin EVA Training for Skylab Here," *Marshall Star* 12 (Oct. 20, 1971): 1; Homer Hickam, "Charlie and the Aquanauts," 52.

Operating the NBS sometimes presented novel problems, but MSFC people invented equipment and techniques to solve them. One of these unique problems involved moving the large mockup structures and precisely positioning them in the tank. An overhead crane travelling on a monorail under the roof of the building lifted hardware into and out of the tank, but moving objects submerged in the water was another matter. The monorail went straight across the tank, but while the overhead crane had ample lifting capacity, it could not reach every part of the tank. A small portable crane was of limited help. In 1969, an employee in the Manufacturing Engineering Laboratory suggested using a doughnut-shaped float and designed one capable of lifting 4,000 pounds, 8 times the capacity of the crane it replaced.[19] Since it floated, it could access every part of the tank and easily move objects from one spot to another. A device of this design continued to be used in the NBS during its nearly 30 years of operation.

Another important invention was the NBS's functional mockup of the Remote Manipulator System (RMS), an underwater version of the Space Shuttle's robotic arm. First used in the NBS a year before the Shuttle's robotic arm was developed, the RMS helped demonstrate the utility of such a device on Shuttle missions. The robotic arm is a multi-section, electro-mechanical arm mounted in the payload bay of the orbiter that is used to accurately deploy and retrieve payloads on orbit while its payload specialist operator controls it from safely inside the cabin. The history of the RMS is another example of the resourcefulness of the NBS staff.

Long before the Space Shuttle, in the days of the orbital workshop program, Hans Wuenscher of Marshall's Manufacturing Engineer Laboratory conceived a manipulating device to aid in assembling structures in space. Called the "serpentuator," because of its snake-like shape, the device was intended to handle tools, equipment, and men in space. One problem faced by its developers was how to test it. Because it was designed for weightless space, it could not even support itself against Earth's gravity, much less function. It was perfect for an early functional test of neutral buoyancy, and around 1967, a small serpentuator was built and tested in the neutral buoyancy tank that preceded the NBS.[20] In 1971, Marshall contracted with Bell Aerospace Company to design a remote maneuvering unit called the "teleoperator" for the Space Shuttle and other future programs. It used an air-bearing platform to simulate space rather than water immersion. One of these was built and studied at Marshall, but neither the serpentuator nor the teleoperator went

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[19] "Four Employees Honored for Cost Reductions," *Marshall Star* 9 (February 11, 1969): 2.
[20] "Snakes Alive! Serpentuator to Extend Reach in Space," *Marshall Star* 7 (July 26, 1967): 1, 10.

beyond the test stage.[21] Canada finally proposed a remote manipulator for the Space Shuttle that ultimately proved successful, but the whole remote-operation scheme had to be tested.

The NBS staff began by salvaging pieces of the existing test manipulators and constructed a Remote Manipulator Simulator (also known as RMS). Once a new mockup of a Shuttle cargo bay was installed in the NBS, they installed the RMS mockup in it. It went into operation in September. 1980[22]

The RMS was remotely controlled by someone outside the water, just as the Shuttles' robotic arm would be operated from inside the spacecraft. While the simulated structure did not function exactly like the robotic arm and was difficult to keep neutrally buoyant, it still simulated the operation of the robotic arm fairly well, and it quickly demonstrated the value of the arm. An improved version of the device, called RMS-II, was built in 1993 to make training more realistic. Built specifically to train for making repairs to the Hubble Space Telescope, it included an operator control station on Level 3 that duplicated the orbiter's controls. The RMS-II was designed by Sverdrup Technology, Inc, fabricated in the Huntsville area, and assembled and tested by MSFC people.[23]

Another invention fine tuned in the NBS was the close-out video camera. Recording an entire EVA task on orbit, showing before and after conditions, was highly desirable so engineers could review and analyze the procedure after the flight. But the astronauts were already too busy to spend time and effort taking video. A procedure for doing this, which involved including the camera in the toolkit on the robotic arm, was devised and tested in the NBS using the RMS-II. These tests showed how the camera could be integrated with the arm to free the astronaut outside of that task. This process was adopted for Shuttle missions and became an important means for evaluating spacecraft conditions.[24]

Space Shuttle crew members practiced EVA tasks for other missions in the NBS as well. Astronauts trained there to repair the guidance system of the Solar Maximum Mission spacecraft, a satellite designed to investigate solar phenomenon, particularly solar flares, that was launched in

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[21] "Bell Studies 'Teleoperator" Under Marshall Contract," *Marshall Star* 12 (Oct. 13, 1971): 2.
[22] Charles Cooper, interview, Jan. 14, 2008; "Hi-Fi Cargo Bay Mockup is Being Installed in NBS," *Marshall Star* 20 (Oct. 24, 1979): 2; "Cargo Bay Mock Up Additions," *Marshall Star* 20 (Feb. 27, 1980); "Structure Deployed by Remote Manipulation System," *Marshall Star* 21 (Oct. 2, 1980): 4.
[23] Paul Dumbacher, interview Jan. 16, 2008; "Improved NBS Makes Training More Realistic," Marshal Star 34 (Oct. 6, 1993): 1, 3.
[24] Paul Dumbacher, interview Jan. 16, 2008.

1980. This was the first attempt to fix a spacecraft in orbit, and one of them practiced with the simulated Manned Maneuvering Unit.[25] The crew successfully made the repairs in 1984. NASA and aerospace contractors also used the NBS to test construction techniques for the International Space Station (ISS), techniques that rapidly increased in complexity. The method to transfer a robotic arm from a Shuttle orbiter to the ISS was validated in 1995.[26] In 1996, a high fidelity mockup of the Z-1 truss segment of the ISS, which housed the communications and tracking, attitude stabilization, thermal control, and electrical power distribution systems, was tested in the NBS. The tests also evaluated the use of mobility aids, handling of equipment, use of foot restraints and hand holds for space walks during Space Station truss assembly.[27]

While test operations were unique and challenging, the NBS staff also looked for ways to make their facility more efficient to operate as well. Maintaining water quality and temperature remained a challenge throughout the NBS's life. The filtration and chemical-treatment systems worked well, but they required frequent attention. Keeping more than 1 million gallons of water in the tank between 85 and 90 F for diver comfort and safety required a great deal of energy. In 1980, MSFC engineers tried to reduce the energy consumption by installing solar collectors on the roof of Building 4705 to provide some of the energy needed to heat the water. This system apparently did not work as well as hoped or became too expensive to maintain, since it was taken out of service about 1990, after which all of the necessary heat again came from a central steam plant.[28]

The NBS remained in active service until NASA's Johnson Space Center, which had long wanted its own underwater microgravity simulation facility for training astronauts, finally managed to obtain funding to construct a larger facility in Houston, but this did not happen all at once. In 1980, JSC managed to get funds to build the Weightless Environment Training Facility, a smaller training pool.[29] While JSC then became the principal site for underwater astronaut training, the NBS continued to provide astronaut training in situations that involved large mockups. Only after the International Space Station received significant funding in the late 1980s was Johnson able to justify the large facility it wanted. After it became clear that the ISS would have to be assembled on orbit,

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[25] Tim Tyson, "Solar Maximum Mission Repair Procedures Tested at Marshall" *Marshall Star* 23 (May 4, 1983): 1.
[26] From NASA webpage, http://www.msfc.nasa.gov/news/news/photos/2001/photos01-142.html.
[27] NASA by Michael Braukus, Steve Roy, Kyle Herring, "Space Station Truss Tested in Neutral Buoyancy Simulator," http://findarticles.com/p/articles/mi_pasa/is_199606/ai_891697618.
[28] "DOE Approves 3 New Solar Projects Here," *Marshall Star* 20 (July 9, 1980): 1; Paul Dumbacher, interview January 14, 2008.
[29] Homer Hickam, "Charlie and the Aquanauts," 52-3.

something that would involve large structures and a great amount of EVA time, JSC began to study and then design a new, larger neutral buoyancy facility. This new facility, the Neutral Buoyancy Laboratory (NBL), was completed at the Sonny Carter Training Facility near JSC in January 1997. The Neutral Buoyancy Laboratory is much larger than the NBS. Its pool (half above ground and half below) is 102' wide, 202' long, and 40' deep, holding 6.2 million gallons of water. This is twelve times larger than the Weightless Environment Training Facility and over four times the volume of the NBS.[30] It could hold the very large mockups expected for the ISS and, thus, simplify the logistics of astronaut training.

Once the NBL became operational, NASA closed the NBS. The tank was drained, and some of its support hardware was sent to JSC, but most of the facility was left in place. To minimize deterioration and reduce on-going maintenance costs, joints in piping systems near pumps and other primary water treatment and control hardware were unfastened and separated to allow air circulation and prevent retention of stagnant water. While the tank and remaining equipment are in good basic condition, and it would be possible to reactivate the facility, the expense required to do so, along with upgrades to monitoring, instrumentation, and support systems, makes such a reactivation unlikely.

For about a dozen years, the NBS was NASA's only dedicated facility for neutral buoyancy simulation, and it remained NASA's largest one until 1997. In recognition of its numerous contributions to manned space flight, the Neutral Buoyancy Simulator was designated a National Historic Landmark in 1985.

3. Operations

While every test program in the NBS was unique, much of the basic operating procedure remained fairly constant throughout its life. With the inherently hazardous nature of the underwater environment, coupled with the numerous opportunities to accidently tear through a space suit or injure a test participant, safety was paramount, just as it would be on orbit. Two types of people were inside the tank during tests: test subjects ("simulated astronauts," as the *Marshall Star* called

[30] NASA, "Home of the Nation's Astronaut Corps," http://www.nasa.gov/centers/johnson/about/history/jsc40/jsc40_pg6.html (accessed January 10, 2008).

them, or actual astronauts), and the scuba divers who supported them.[31] The NBS was equipped to support four test subjects at a time, but most tests had one or two subjects. Support personnel remaining outside the tank included NASA and contractor people controlling and monitoring the test in the control room, technicians handling the breathing-air system and other support equipment, other technicians to assist the test subjects with their spacesuits, and those responsible for day-to-day operation and maintenance of the NBS's water filtration and treatment systems, cranes, and other associated equipment.

Originally the NBS had a full-time staff of about 22 people. When Skylab astronaut training began in 1971, U. S. Navy divers trained for recovering Apollo spacecraft after splashdown came to Huntsville to serve as safety divers for the NBS. Navy divers on temporary assignment to NASA continued to work as safety divers at the NBS through the 1970s.[32] When the tours of duty ended, around 1980, the NBS staff came up with a new method for obtaining divers: recruiting and training Marshall employees as volunteer divers. These were individuals holding regular jobs at MSFC who went through training to gain diver certification. Training covered scuba diving, pressure suits, safety, and station operations. To be a test subject, a diver received additional training in spacesuit operations and emergency procedures. They served in the NBS on an as-needed basis, when their schedules permitted. The plan worked well, and eventually the NBS had a roster of over 150 volunteer divers to draw upon.[33]

For every test subject in the tank, there were several support divers. Each test subject was watched by two safety divers. The safety divers put weights on the spacesuits when the test subjects entered the tank, and they also looked after the test subjects, helping them if they became ill and keeping their umbilical lines from getting tangled. Another position was utility diver, individuals who followed test subjects and handed them tools. Small objects like tools were not made neutrally buoyant and would sink if dropped, although they would float in space; by handing the test subjects tools, the utility diver gave them a more realistic experience and no time was lost retrieving tools. The water safety diver kept an eye on the test overall. A camera operator swam in for close-up shots that the wall-mounted cameras could not capture. The NBS staff attempted to make a robotic camera, but its umbilical would get tangled in the mockups and other umbilicals, so the idea was

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[31] "Workshop-ATM Tasks, Gear Are Studied Underwater," *Marshall Star* 9 (Jan. 15, 1969): 2.
[32] Christine Duncan, "Navy Divers on Duty at Marshall's NBS," *Marshall Star* 18 (Nov. 16, 1977): 4.
[33] Paul Dumbacher, interview January 11, 2008; "Qualified Divers Needed at MSFC," *Marshall Star* 21 (April 29, 1981): 4. Around 1993, the NBS had a staff of about 17 (MSFC, "Neutral Buoyancy Simulator," n.d.).

abandoned. For a two-person test and a three-hour dive, six support divers were usually required. The number per test subject increased when dives lasted for six hours.[34]

For the sake of the divers, the water temperature in the tank was maintained at 85-90 F. While the test subjects in the spacesuits were protected from cold, the divers were not, and with the warm water they could remain in the tank for the duration of the tests without getting hypothermia.

At first, all the test subjects and divers, as well as astronauts, were male, but in 1975, women worked for the first time as test subjects in the NBS, a few years before women were chosen as astronaut candidates. The two female test subjects were Marshall employees who were planning experiments for the Space Shuttle.[35]

A typical test involved mockups and tools, test subjects or astronauts, support divers, and NBS staff members who handled the monitoring instruments, pressure suits, and life support. Before each test, the NBS staff would prepare the underwater mockups and make sure all tools needed for the test were in place. The morning of the test would begin with a briefing for the divers that covered the purposes and procedures of the test. Then the divers would get into their gear, test subjects would don their suits, and all would go to the top deck. Following safety checks, divers and test subjects usually entered the water by a stairway. Each would descend the stairs into the water to a platform about 15' below the surface. Here, a safety diver would put lead weights on the test subject(s). These would be placed as needed at the subject's chest, back, wrist, leg, or ankle according to the subject's weight, so that he/she was "weighted out," or "neutralized." The test subject could not swim in the spacesuit, so once neutralized, the divers would move the person to the worksite. Safety divers stayed close at all times. The client for the test would watch the proceedings on video in the control room and remain in voice communication with the test subjects throughout the duration. During the test, the test subject's actions would be filmed and all conversation between the subject and observers recorded. After completing the test operations, the subject(s) exited the tank by the reverse of the entry process. In later years, entrance and exit became somewhat easier after a mechanical lift was installed for the test subjects so they would not have to use the stairs. The lift, a modified version of a device used in warehouses to move boxes,

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[34] Vyga Kulpa, MSFC, former NBS facility and test director, interview January 10, 2008; Paul Dumbacher, interview January 11, 2008; Joe Dabbs, "Neutral Buoyancy Simulator Has History of Invaluable Service to Marshall and the Nation's Sp[ace Program," *Marshall Star* 31 (Feb. 19, 1992): 3.
[35] "Another Male Stronghold Crumbles," *Marshall Star* 15 (May 14, 1975): 1.

raised the subjects off the deck then rotated around to place them over the water and lowered them down into it. It also raised them out of the water.[36]

Although the tank was indoors, the surrounding building was metal, making it somewhat susceptible to lightning strikes. Thus, it was potentially dangerous to work in the tank during a thunderstorm, and the staff had to be attentive to weather conditions. At first, they used a window in the roof of this otherwise windowless structure to watch for flashes and then count the seconds between the flash and when they heard the ensuing thunder to estimate how far away the lightning was. Later, a sensor network and computer program was developed to detect lightening.[37]

The test subjects wore bulky, pressurized spacesuits, very much like astronauts wear in space, as these were critical to achieving realistic simulations. The suits were somewhat modified for the NBS and provided with breathing air through umbilical lines. Flight-ready spacesuits were, and still are, extremely expensive, and at the start of the space program, Apollo suits were scarce. In its early days the NBS staff adapted U. S. Navy high-altitude "Arrowhead" flight suits for underwater duty. They were selected primarily because they were already waterproofed to protect pilots should they bail out over water. Eventually, the NBS was able to obtain Apollo spacesuits and, as the space program evolved, updated versions became available. In 1982, the Space Shuttle suit with its large backpack, called an Extravehicular Mobility Unit (EMU), was first used in the NBS.[38] In the 1990s, the NBS got hand-me-down suits called "Class III," meaning they had a seen some wear and perhaps leaked slightly, but these were adequate for Earth-based tests. Supplied with air, test subjects in these suits could stay in the tank 3 hours and 15 minutes.[39]

In 1993, the NBS began using Nitrox to permit longer dive times. These were needed for tests of procedures being developed to repair the Hubble Space Telescope. These EVA repair tasks would exceed 3 hours, the time allowed underwater while breathing air, and the team needed to have the test subjects work the full time required for the tasks in order to study how they would hold up and perform for the duration. The NBS staff ordered a design and engineering analysis of Nitrox, a mixture of nitrogen and oxygen like primary gasses in air, but with about twice the oxygen concentration. After concluding that Nitrox would safely meet the requirements, test subjects began

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[36] Paul Dumbacher, interview January 11, 2008; Vyga Kulpa, interview January 10, 2008.
[37] Vyga Kulpa, interview January 10, 2008.
[38] Joe Dabbs, "Neutral Buoyancy Simulator Has History of Invaluable Service to Marshall and the Nation's Sp[ace Program," *Marshall Star* 31 (Feb. 19, 1992): 2; "Shuttle Suit Demonstrated," *Marshall Star* 23 (Oct. 6, 1982): 2.
[39] "Heckman Gives As Much As He Receives From Sports." *Marshall Star* 8 (April 10, 1969): 3; Paul Dumbacher, interview January 11, 2008.

to use it during their long dives. Breathing Nitrox, a subject could remain submerged for up to 6 hours, ample time to simulate the entire EVA.[40]

[40] Paul Dumbacher, interview Jan. 16, 2008.

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