MARVIN F. CLARKE
General Electric Co.
Philadelphia, Pa.

Underwater Simulation of a Lunar-Surface Traverse

This paper is a summary presentation of some of the work accomplished by the Missile and Space Division of the General Electric Co. during the past 18 months. Particular emphasis is placed upon its possible significance with respect to man's capabilities and limitations when he first attempts to walk on the lunar surface.

As a supplement to the basic analytical approach toward determining the problems which man will encounter when he makes this first lunar walk, the General Electric Co. has developed underwater simulation techniques which provide insight into some of the specific problems to be expected and potential means to resolve or ameliorate such problems. The underwater simulation techniques are based upon the crew performance of simulated mission tasks in a partial-gravity or zero-gravity condition when a specially designed backpack is used to provide life support and space-suit pressurization and to maintain constant volume displacement of the underwater subject. The backpack also provides recorded measurements of key biophysical parameters.

A simulated lunar traverse was made over an 80-foot course on the bottom of the bay at the General Electric Co. Underwater Test Facility. Two different subjects in pressurized space suits in a simulated ⅙-gravity condition were used. Both subjects demonstrated their inability to walk purposefully under these conditions. The addition of a walking staff as a mobility aid made traverse of the simulated lunar terrain possible though still difficult.

INTRODUCTION

When man first lands upon the Moon and leaves his spacecraft to explore the lunar surface, he will be faced with many conditions never before experienced. One of the most significant of these new conditions will be the reduced gravity field on the lunar surface. Because of the smaller size of the Moon with respect to the Earth, the gravity field at the lunar surface is only 0.165 of that field present at the Earth's surface. Thus a man's weight on the surface of the Moon will be approximately one-sixth of his weight on Earth. This is also true for his spacecraft and for all of the equipment and experiments which he brought with him.

This apparent reduction in weight on the Moon as compared with similar weights on Earth has led to many interesting speculations as to man's potential physical capabilities on the lunar surface. In general, it has been assumed that since man developed his muscles in an Earth environment he would be capable of a greatly increased physical performance on the Moon where his weight would be much less than that which he normally experienced on Earth.

Since man is so adaptable to new situations and environments, it is quite possible that he will eventually move across the lunar surface in great leaping strides, but it appears likely that he will first have to learn to walk. The reasons for this become apparent when one considers the physical parameters involved. Although a man's weight appears to be less on the surface of the Moon, his absolute mass has not changed. Thus, if we consider a man who is trying to move in a horizontal line on the lunar surface, it will require just as much force to start, stop, or turn at a given rate as it did on Earth. Similarly, the momentum he will develop (and the velocity, since his mass is constant) is a function of the force times the time applied, or the total impulse. Thus, if he jumped straight up, he would leave the surface at a velocity similar to that on Earth, but, because of the lower gravity on the Moon, he would go much higher and would remain in the air much longer than he would on Earth. This timing change is one of the factors which will make it difficult at first for an astronaut to walk on the Moon.

When a man walks on the Earth, he not only leans forward but also rocks from side to side as he swings one leg after the other and shifts his weight from one to the other. The combination of these movements, properly timed in a coordinated sequence, takes a while to learn. It is reasonable to assume that, if the time constants varied significantly, as they would if the man were trying to walk on the lunar surface instead of on Earth, man may, and probably will, have difficulty when he first tries to walk on the Moon.

The above analogy is a greatly oversimplified case, but it serves a useful purpose by highlighting a particular part of the total problem which may be a potential source of trouble when man first tries to walk on the Moon. There are obviously many such potential trouble sources involved in the physical locomotion of a space-suited astronaut over the lunar surface and his performance of all the varied man/machine tasks involved in space voyage and lunar exploration and experiment activities.

Crew/system performance in manned space systems under partial-gravity and zero-gravity conditions can be investigated using an underwater simulation technique. It provides one of the more useful and cost-effective methods of empirically answering fundamental questions related to human performance and the development of equipment needed to optimize man's performance in space.

FACILITIES

In order for the General Electric Co. to put into operation a facility to accommodate large existing structures (such as the Saturn S-IVB workshop) on a timely economic basis, it was imperative that a natural site be selected. High capital expenditures and long leadtimes ruled out the possibility of constructing a large tank facility. Furthermore, a natural site was desired which would provide a relatively unlimited growth possibility.

Mandatory requirements for the facility were:

(1) Adequate space for whole task simulation which would accept a minimum 55-foot-long by 22-foot-diameter structure with growth possibilities.

(2) Clear water for ease of vision and to facilitate underwater photography.

(3) Calm water to facilitate surface operations and to minimize underwater currents and disturbances.

(4) Warm water (minimum 78° F) to permit year-round operations with efficiency and comfort.

(5) Ready access to aerospace and industry centers and to support services.

After a careful review of available locations, Buck Island, the site of a former U.S. Navy UDT training area near St. Thomas, V.I., was chosen. Buck Island provides a cove approximately 700 feet in diameter with a sandy bottom. The cove is sheltered on the lee side of the island from the predictable easterly trade winds. The water is warm and clear throughout the year, and sufficient light is available for good underwater photography. The maximum tidal variation is less than 1 foot. The Buck Island site is sufficiently remote from St. Thomas to discourage curiosity seekers but still not so far away as to cause operational problems.

The underwater test area of the General Electric Co. is located within a sheltered cove of approximately 10 acres on the western side of Buck Island. This island is located 4 miles off the south coast of St. Thomas, the most populous of the Virgin Islands, and near the entrance to the harbor of Charlotte Amalie, the largest city in the islands.

As shown in figure 1, the water depth in the primary simulation area is 28 to 29 feet and there are additional test areas surveyed in the 15- and 20-foot ranges. The cove floor in these testing areas is composed of white sand. It is quite level and relatively free of rocks and marine life. Water temperature is a rela-

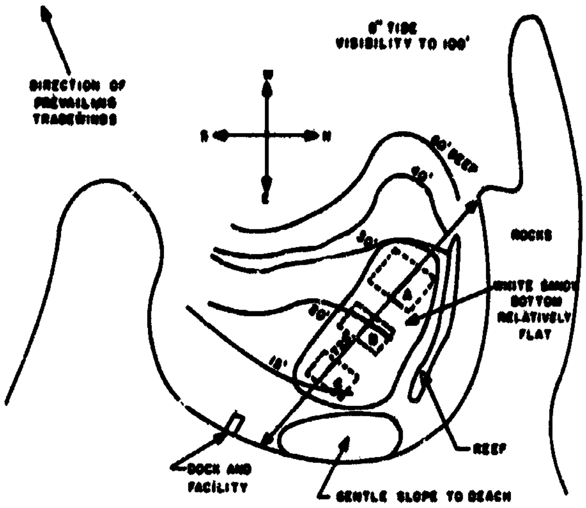

FIGURE 1.—Schematic diagram of the General Electric Co. underwater test facility at Buck Island, V.I. *A*, 28-foot test area; *B*, 20-foot test area; *C*, 15-foot test area.

tively constant 78° to 82° F. Underwater visibility approaches 100 feet permitting detailed underwater photography without the need of artificial light under most conditions.

An operations building has been constructed on the foundation of an old concrete pier approximately 300 feet from the primary underwater test area. This structure, with dimensions of 12 by 20 feet, contains the monitoring, recording, diving, and medical equipments, general office space, and comfort facilities. A covered access deck extends around three sides of the building with a boat dock attached to the west side facing the testing areas. A platform extends into the water from the dock to permit ready access to the water for both test personnel and pressure-suited test subjects. The building is lighted and air conditioned and draws its power from two 3000-watt gasoline generators located on the roof.

A hexagonal observation platform located 40 feet from the primary simulation area permits direct viewing of test operations and provides for above-water photography through its six Plexiglas windows located below the waterline. A safety work platform was installed over the primary simulation area. Figure 2 shows the relative locations of the operations building, the observation platform, and the primary test area.

FIGURE 2.—General Electric Co. underwater test facility site.

Boats are available as required to transport personnel and equipment to and from the site. A close working relationship has been established with a local machine shop which is capable of providing speedy fabrication of experimental hardware.

Continuous communications are maintained with the main island of St. Thomas through leased radiotelephone lines provided through the Virgin Islands Communications Corporation. Onsite communications are provided by walkie-talkie units as required.

Although present experimental plans do not require the use of extensive quantities of classified material, arrangements have been made for the protection and safeguarding of any such material that may be required. Arrangements have been made for storage of classified items at the U.S. Coast Guard Station, Charlotte Amalie, St. Thomas.

UNIQUE SUPPORT EQUIPMENT

The changes in lung volumes when a diver inhales and exhales result in changes in his total water displacement and hence in his buoyancy. In order to maintain a constant partial-gravity simulation and, even more important, to maintain a neutral buoyancy to simulate zero-gravity conditions, it was necessary to develop a compensatory breathing apparatus to eliminate these changes.

The General Electric backpack shown in figure 3 was developed for this use. In addition, it also provides the following functions:

(1) Closed respiratory system with carbon dioxide removal and automatic replacement of oxygen consumed.

(2) Space-suit pressurization at selected pressures from 0 to 4 psig above ambient.

(3) Sensing and recording of physiological data such as—

Electrocardiogram
Respiratory rate
Respiratory volume
Oxygen consumption
Deep body temperature

The closed respiratory system has three major advantages over an open-type system:

(1) It eliminates bubbles.

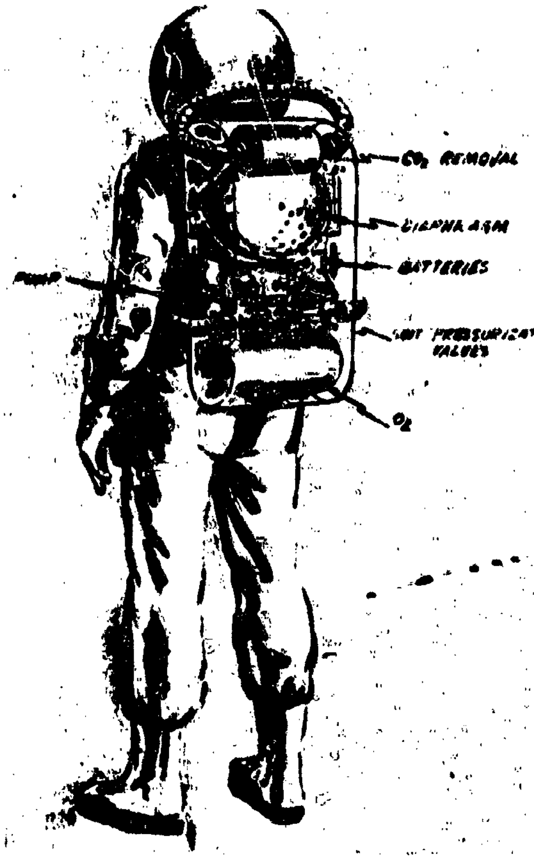

FIGURE 3.—General Electric Co. neutral buoyancy and life-support backpack for underwater simulation of zero-gravity conditions.

(2) It eliminates the cyclic rise and fall of the test subject as a result of inspiration and expiration.

(3) It provides a larger test time between bottle changes, since only the oxygen consumed metabolically need be carried.

Physiological data recorded in the backpack provides a basis for estimating the energy output required to accomplish a given task. The data to be taken include respiration rate, tidal volume, body temperature, electrocardiogram, and oxygen consumption; of these, oxygen consumption is considered to be of primary importance. The signals from these physiological transducers are recorded directly on a Gemini-type biomedical tape recorder which is incorporated into the backpack.

The backpack incorporated a system for pressurizing the space suit so that tests could be conducted with a pressure-suited subject. A water pressurization system was selected for space-suit use in underwater simulation for the following reasons:

(1) An air-pressurized suit must be brought to neutral buoyancy by distributing weights over the suit surface. These weights (of the order of 100 to 200 pounds, depending on the subject and suit size) are difficult to install so that the test subject is truly neutrally buoyant in any orientation and impose a safety hazard should the suit lose its pressure.

(2) Air leaks from air-pressurized suits cause distracting bubbles and provide orientation cues to the test subject.

(3) If the test subject, in water, works in an inverted position (head down) in an air-pressurized suit, he will experience the same effect as if he were hanging by his feet on land because the air pressurization level is constant throughout the suit.

(4) Changes of depth will cause variations in an air-pressurized suit delta pressure and will require the addition or venting of air from the suit.

ORBITAL WORKSHOP SIMULATION

Operation of the presently conceived Apollo Applications Program (AAP) orbital workshop requires extended and complex astronaut performance after orbit insertion. The astronauts' tasks will include passivation of the Saturn S-IVB spent stage, transfer of equipment from its launch location through an airlock and into the spent-stage hydrogen tank, and erection and operation of this equipment. Implicit in these tasks are basic requirements for electrical, hydraulic, and mechanical connection; operation of controls, hatches, fasteners, and restraint systems; and the controlled transport of large pieces of equipment through relatively long distances and large volumes.

The tests conducted by General Electric Co. in the winter of 1966-67 were primarily exploratory and attempted to develop guidelines for crew performance and equipment design. They did identify basic problems, either of a human or an equipment performance nature, which need further understanding and which must therefore be simulated more completely in the future. The exploratory tests conducted included the following:

(1) Hydrogen tank cover removal

(2) Installation and evaluation of mobility aids

(3) Transfer of large bulky equipment

(4) Erection of an experiment console

(5) Erection of primary partitions

At the time these tests were being planned, the AAP orbital workshop configuration in orbit was similar to that shown in figure 4. A cutaway of this configuration model is shown in figure 5. An underwater test structure with this configuration was built of aluminum rings and screen wire, in full scale, and implanted at the Buck Island test facility. Mounted on a supporting bed which rests directly on the level sandy cove bottom, the underwater test structure (fig. 6) is a full-scale geometric duplicate of the—

(1) Saturn S-IVB spent stage

(2) Equipment section (forward of the LH_2 tank)

(3) Adapter section (to the SLA panel joint)

(4) Airlock and docking adapter

(5) Pertinent task equipment and mobility aids

Measuring 22 feet in diameter by 52 feet in overall length, the simulator shell is a skeleton

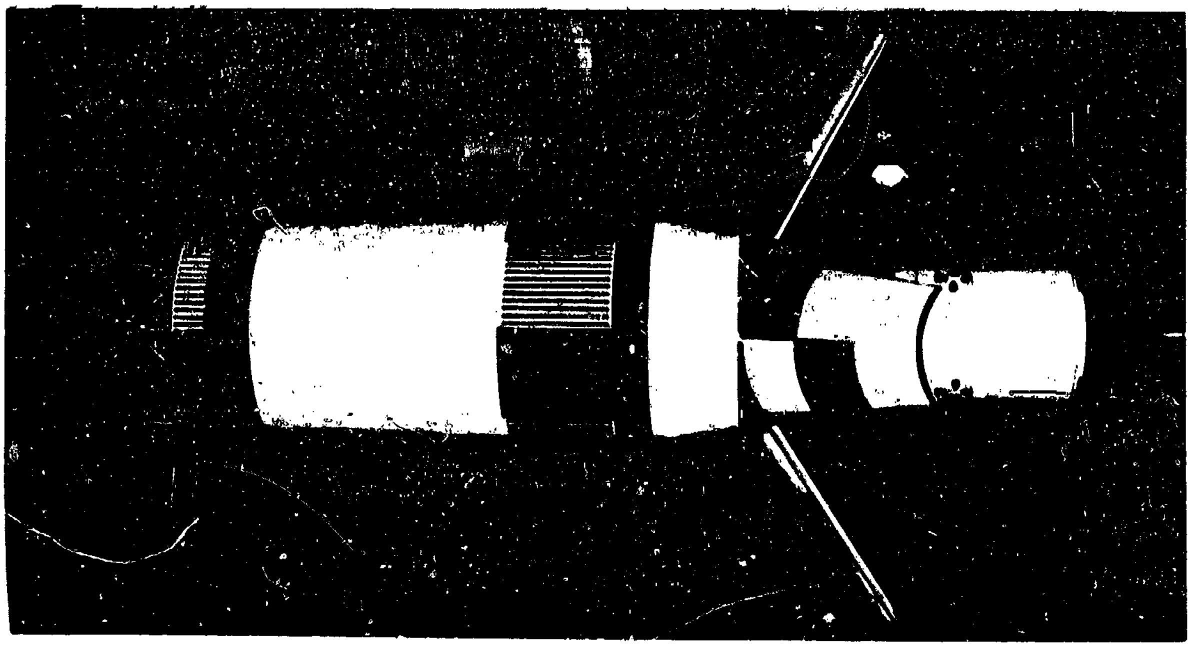

FIGURE 4.—AAP orbital workshop (late 1966 orbital configuration).

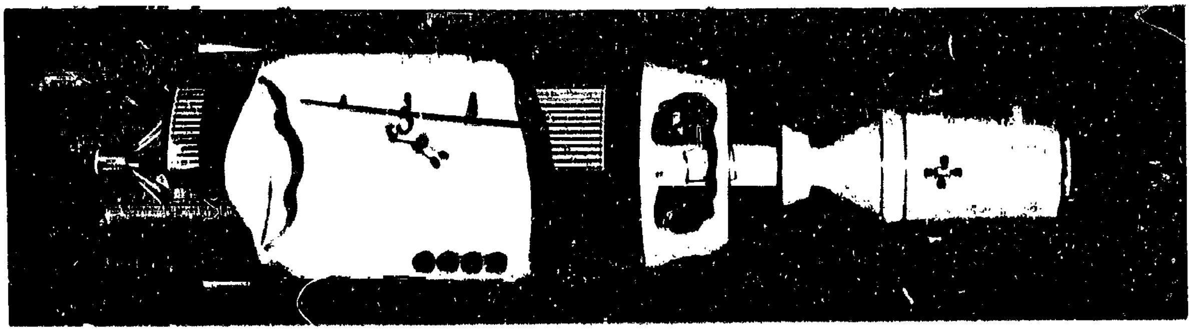

FIGURE 5.—Cutaway view of the AAP orbital workshop (1966 orbital configuration).

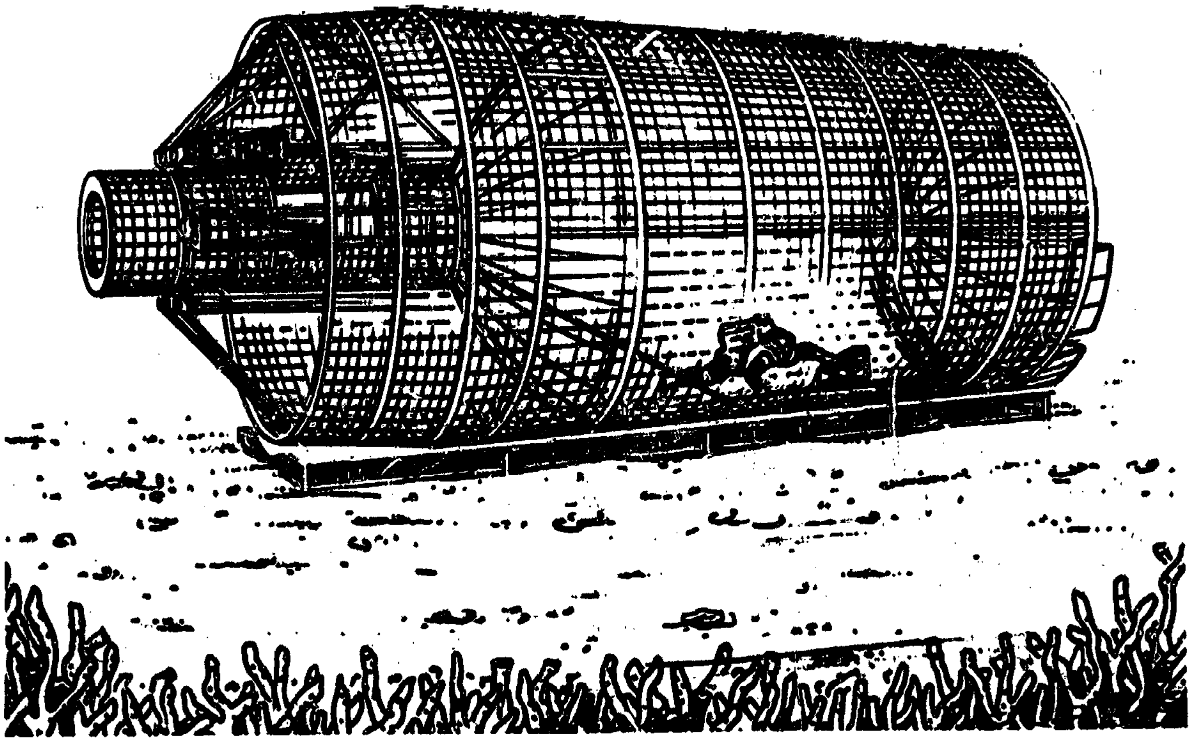

FIGURE 6.—Underwater simulation mockup of the AAP orbital workshop as used by General Electric Co. in 1966–67 tests.

framework of aluminum rings and stiffeners covered with a 4- by 4-inch grid of wire mesh protected from corrosion by a high-visibility, yellow-plastic-base marine paint. Total weight is 7500 pounds. The open design was dictated by the nature of the work, which required maximum exposure for photographic records, test direction, observation by safety divers, solar illumination, and minimum resistance to water motion in the event of turbulence.

The task simulations were planned around the actual tasks which will have to be performed in order to passivate the Saturn S-IVB spent stage and to activate and inhabit the orbital workshop after it is in orbit. Specific tasks were devised around the equipment involved.

Saturn S–IVB Spent Stage

The hydrogen tank, enclosing a volume in excess of 10 000 ft^3, constitutes a major portion of the structure. Included in this item are the three largest internal items which would help or hinder test subject activity within this chamber:

(1) A 34-foot-long propellant utilization probe

(2) An LH_2 vent pipe

(3) Six 23-inch-diameter helium storage spheres

Also included for use in attaching mobility aids, compartmentizing partitions, and consoles are the 112 NASA-type equipment attachment fittings preinstalled in the liquid hydrogen tank of this S–IVB.

In the compound curvature area, where the LH_2 and liquid-oxygen tanks join, are four boattail extensions on which are mounted hardware simulating:

(1) Chilldown pump
(2) LH_2 feed line and antivortex screen
(3) LH_2 chill return
(4) LH_2 fill line and diffuser

As part of the experimental task sequence, these units must be sealed before final pressurization and habitation in the spent-stage LH_2 tank.

Airlock

The airlock is basically a tunnel connecting the Apollo command module to the S–IVB spent stage (SA 209 configuration). This unit measures 65 inches in diameter by 15½ feet long, and follows the design originally proposed by McDonnell Aircraft Co.

Mobility Aids and Task Equipment

The mobility aids provided were, in general, polypropylene rope with quick-connecting clips located at predetermined intervals. Polypropylene, being less dense than water, tended to overcome the clip weight and thus effectively made these aids neutrally buoyant to transport to their positions.

In addition, a three-section telescoping rod was constructed to traverse the distance between the forward-dome manhole and the closest attachment points. After it is extended to its 15-foot length, it is locked in position, and a clip mounted at the forward end secures it to one of the equipment attachment fittings.

The console was simulated by a skeleton framework of aluminum to minimize drag, polyurethane was bonded to the inside of the framework to provide neutral buoyancy, and a Plexiglas sphere of appropriate size was suspended within the framework and allowed to fill with water to provide the necessary mass equivalent.

For tasks such as fastening the console and removing the chilldown pump, appropriate tools are provided, including blade- or socket-type drivers, a ratchet wrench, cam-actuated sealing plugs, blind flanges, and numerous other items. Several types of tethers are provided to determine their usefulness. These included wrist or waist attachment loops and Velcro loop and pile on the tool belt. An equipment storage container was also provided.

The Saturn S–IVB stage was chosen as a basic simulation tool when the Buck Island program was first conceived. The rationale behind this decision was twofold: (1) by using the S–IVB, whole task simulation of a large structure could be demonstrated for the first time; and (2) realistic operations and task ground rules concerning an established ongoing space project could be provided. The requirements for crew operations in the S–IVB orbital workshop are far more complex than those established for space missions to date. For the first time, the astronaut is required to perform assembly, erection, checkout, and maintenance and repair tasks which will have long-range applications to the future development of the U.S. space-flight program.

In order to prepare the S–IVB spent-stage hydrogen tank for shirtsleeve occupation, a passivation sequence must be accomplished which includes the sealing of potential leak points at the common bulkhead. The astronaut must translate from the airlock down into the hydrogen tank and thence to the LH_2 chill pump inlet. The top portion of the pump inlet must be removed and replaced with a blind flange which is bolted in place. The astronaut must then translate to the fuel feed line, remove the antivortex screen, and install an expandable plug in the feed-line opening. He must then translate to the LH_2 chill return line, install an expandable plug, and then translate to the LH_2 fill line and diffuser, unbolt the diffuser, and insert an expandable plug in the fill line, and then return to the airlock. The task is accomplished with the astronaut in a pressure suit and with the use of ordinary handtools.

The elemental task steps and times to complete are shown in table 1.

TABLE 1.—*Stage Passivation Task Results*

Subtask	Measured times for simulated task, min	Projected times for actual task, min
Insert plug in LH_2 feedline, actuate and lock handle	0.5	1
Realine cover over opening in antivortex screen and secure with 3 screws	5	5
Translate to LH_2 chill return	.5	.5
Remove expandable plug from stowage container	.5	1.5
Insert expandable plug in LH_2 chill return, actuate handle, and lock	.5	1
Translate to LH_2 fill line and diffuser	.5	.5
Remove 4 bolts holding diffuser in position	3	3
Remove diffuser and place in stowage container	.5	.5
Remove expandable plug from stowage package	.5	1.5
Insert expandable plug into fill line, actuate handle, and lock	.5	1
Translate to airlock via mobility aid	.5	1.5
Total task time.	35.5	70

The following conclusions were derived from observations of subjects, safety divers, and the test conductor:

(1) The task elements proved to be quite repetitious and, as a result, boring.

(2) Reactionless power tools or ordinary power tools would have cut down the time needed to perform the tasks but could in no way be considered mandatory.

(3) Some form of quick-release tether system is mandatory at each work site.

(4) Fixed mobility aids are required for personnel transfer.

(5) The task was accomplished with reasonable ease and resulted in little fatigue. Access to all fasteners was adequate.

(6) Properly designed tool and equipment restraints and containers are mandatory.

(7) Projected time to complete task in orbit without using power tools is 70 minutes. The use of power tools to remove the 40 bolts on the antivortex screen cover would probably cut this time to 42 minutes. (The simulator had only six bolts.)

(8) Optimum translational velocity appeared to be on the order of 1 ft/sec or less.

LUNAR-SURFACE TRAVERSE

An underwater simulation of a lunar-surface traverse was accomplished at the Buck Island test facility in early 1967. An 80-foot-long course was selected at the bottom of the bay which included various degrees of surface roughness, slope, and texture such as might be encountered on the Moon. In addition, the course included a fixed ladder which the astronaut must ascend and descend as a part of the course to simulate his exit and reentrance to the Lunar Excursion Module. The simulated lunar traverse task included moving 80 feet over the different types of surface, climbing up the ladder and descending again, and return to the starting point.

The test subjects were ballasted by the addition of lead weights to simulate the 1/6 g on the Moon. This was accomplished by weighing them, fully equipped, in air, then weighing them again immersed in the sea, and adding weights to their harness until the 1/6 g negative buoyancy was achieved.

The two primary test subjects used for these tests were a test pilot and an athlete. Both were experienced scuba divers and both had had extensive previous experience in underwater simulation both with and without the backpack.

The lunar-traverse task was first performed using the backpack but no space suit. The test subjects were suitably weighted. Under these conditions, the test subjects were able to traverse the course without undue difficulty.

The lunar-traverse task was then attempted with the test subjects using the state-of-the-art space suit pressurized with water to 3.7 psig and the backpack, as shown in figure 7. The test subjects were ballasted to achieve a negative buoyancy of 1/6 g.

Surprisingly, when the astronauts tried to walk on the bottom of the bay in the pressurized space suit, they fell over to the side. Neither test subject was able to maintain his balance and walk purposefully in this fully suited 1/6 g condition. The problem appeared to be a strong tendency of the subjects to overcontrol when they were shifting weight from one leg to the other in order to take the next step. Hampered by the resistance of the pressurized space-suit joints, the test subjects were unable to maintain the fine positional control and muscular coordination necessary to walk purposefully under these conditions, particularly upgrade. The difficulty in rising in a pressurized space suit after a fall presented another problem area.

It was found that the use of a walking staff provided the test subjects with a mobility aid which did make it possible for them to traverse the lunar course and return. The average time to traverse the course, climb and descend the ladder, and return to the starting point was 4 minutes and 45 seconds. Thus the average velocity was approximately 0.5 ft/sec, or 1/3 mph.

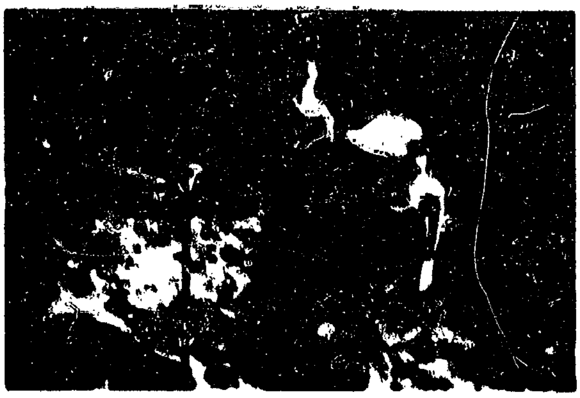

FIGURE 7.—Simulated lunar traverse.

Both test subjects found walking somewhat hampered by the reduced downward visibility in the space suit. It was difficult for a subject to look down at his own feet and see the next place where a foot would be planted. This resulted in some stumbling over small objects which would normally be avoided.

The reduced-gravity simulation resulted in a marked decrease of pressure between the test subject's boots and the ground surface. This was expected, and it had the expected result of reducing the traction by reducing friction between the boot and the ground. Similar experience was had during 1/6 g Keplerian flights. At 1/6 g, the lower limit for surface traction for walking is approached. This may be compared to the feeling one gets when he tries to walk on ice. The test subjects did notice this effect during the lunar-traverse simulation. The selected traverse path included a long slope of approximately 10° which they covered; however, a 2-foot-high boulder was an object to be avoided rather than surmounted.

One of the significant factors noted during the simulation was the tendency of the test subject to overshoot his target if he tried to hurry. This is not surprising if one considers that the test subject's apparent mass, caused by his backpack, his space suit, the pressurization water in his space suit, and the ballast, is much higher than that he is used to normally and his traction is much less than normal. Consequently, when he does get up to reasonable speed, he finds it difficult to stop again.

Although both test subjects were in excellent physical condition, they both found the lunar-traverse task to be very tiring. Of course, this physical tiring was partially due to the exertions in donning the equipment, checking it out, and getting ready to perform the task.

CONCLUDING REMARKS

The lunar-traverse task was performed to investigate the underwater simulation techniques for astronaut mobility under lunar gravity conditions. It proved to be a useful tool in highlighting potential trouble areas when an astronaut first tries to walk on the Moon. It has aided in the understanding of his physical problems in a way that can seldom be achieved analytically. The results achieved clearly indicate that the astronaut may have to do some relearning before he can walk on the Moon with any ease. The test subjects in our simulation task considered the walking staff to be a mandatory mobility aid. Subjective comparison to 1/6 g Keplerian flights was stated to be excellent.