8. WATER-IMMERSION TECHNIQUE FOR SIMULATION OF INGRESS-EGRESS MANEUVERS UNDER CONDITIONS OF WEIGHTLESSNESS

By Otto F. Trout, Jr.

SUMMARY

A water-immersion technique has been developed whereby a pressure-suited subject, unrestrained by connecting lines and hoses, can simulate maneuvers under conditions of weightlessness in six degrees of freedom. This simulation has been applied to a series of ingress-egress experiments, and some of the results are described in this paper. The results of these experiments indicate that the technique has application to the study of human factors and capabilities in extravehicular space operations and to a determination of design criteria for advanced manned space vehicles and related equipment.

INTRODUCTION

Current NASA studies of manned space stations and other extended-mission space vehicles include requirements for extravehicular astronaut performance in the hard-vacuum, zero-gravity environment of space while encumbered by a full pressure suit. These tasks will include ingress-egress through airlocks, intervehicular crew and cargo transfer, assembly of external equipment and experimental hardware, inspection and maintenance of equipment, and performance of various extravehicular scientific tasks and measurements.

Assessment of available means of simulation of these tasks has shown a definite need for the development of additional techniques. An investigation was therefore undertaken to examine the feasibility of a pressure-suited subject operating in a neutrally buoyant condition in water to study weightless ingress-egress maneuvers through airlock systems. The feasibility of the technique was demonstrated and used to determine problem areas associated with ingress-egress operations. It has proven to be a valuable research tool for zero-gravity simulation where the pressure-suited subject is required to work in confined spaces and where the velocities of the subject are low.

This simulation technique is primarily designed to investigate the external motion performance characteristics of the suited subject in a weightless state, in six degrees of freedom, unrestrained by connecting lines and hoses but does not provide for assessment of internal physiological effects at zero gravity.

The simulation has been applied to a number of ingress-egress problems that include operation through airlock systems, examination of problem areas, motion aids, workspace limitations, equipment sizes, and the study of human factors and astronaut capabilities in a weightless environment.

ZERO-GRAVITY SIMULATION TECHNIQUES

The recent Gemini and Voskhod flights have shown some of the value and feasibility of operations of an astronaut on the exterior of a vehicle. Figure 1 is an artist's concept of an astronaut making egress from the airlock of a manned space vehicle into the hard-vacuum environment in a pressurized suit. The extravehicular operations in which man can effectively be utilized on extended missions include ingress and egress operations through airlock systems, assembly and maintenance of equipment, crew and cargo transfer functions, observation and inspection tasks, and manned experimentation in research endeavors. An important factor in the success of extended manned space missions will be the extravehicular operational performance of suited astronauts in both the routine and emergency modes.

The operational characteristics and work output capabilities of the suited astronauts in the zero-gravity and partial-gravity environments need to be assessed in order to define and develop operational procedures, to obtain anthropometric data for design purposes, to provide specifications for systems design, and to determine man-machine relationships. The interaction of vehicle systems, the size and configuration of airlock systems, the choice of supporting hardware, and the design of extravehicular equipment cannot be specified until the capabilities of the pressure-suited astronaut are determined.

Examination of manned experiments has shown an apparent lack of facilities to develop design data and to simulate the suited astronaut in a tractionless or reduced-traction environment. The principal means of simulation available for studying these extravehicular operations include aircraft Keplerian trajectory, cable and suspension systems, air-bearing platforms, and water-immersion neutral buoyancy. Each of these means of simulation is a valuable tool but has definite limitations. The aircraft flying a Keplerian trajectory is limited to test durations of 10 to 30 seconds. Cable suspension systems and air-bearing platforms restrict performance, in confined spaces, to single planes or to limited degrees of freedom. Water immersion is limited to low velocities because of drag effects. Actual orbital experiments are obviously too costly and complex for obtaining preliminary data. The several means of simulation are often complementary, and valuable data may thus be obtained by performing similar tests by more than one method.

APPARATUS AND TESTS

Because the water-immersion technique appeared to offer advantages for studying ingress-egress operations and was the least developed, an investigation was undertaken to assess the feasibility of operating a pressure-suited subject neutrally buoyant in water with a self-contained breathing apparatus. This research has resulted in a successful technique wherein a subject using a modified Navy Mark IV pressure suit has been able to operate under water in six degrees of freedom for extended periods of time up to $1\frac{1}{2}$ hours, unrestrained by connecting lines and hoses. Weightless simulation by water immersion has often been suggested in the past, but this effort is believed to be the first time that it has been successfully used with a test subject in a fully pressurized suit.

Figure 2 illustrates the pressurization and breathing system of the suit used in these tests. The Navy Mark IV suit was used because of its availability. It was modified by blocking the ventilation system and replacing the oxygen system with a self-contained air supply. High-pressure air is supplied by a 2500-psi storage bottle on the subject's back to which first- and second-stage regulators are connected. A demand regulator in the helmet provides a flow of air into the facial area of the helmet when the subject inhales. Exhalation by the subject causes the demand regulator to close, and air is expelled into the torso of the suit by a valve located in the neck seal. This expelled air acts to pressurize the suit to the level preset on the relief valve. This system effectively provides for breathing and suit pressurization both under water and on the ground.

The validity of the water-immersion simulation was examined by performing a series of water-immersion experiments and comparing them with similar experiments by zero-gravity aircraft flights and ground tests. The aircraft-test results were shown to be comparable to the water-immersion-test results when the movements of the subject were not rapid. Comparable experiments on the ground at full-gravity conditions with the same subjects and equipment have shown that the ground results are not comparable for studies of the weightless ingress-egress problems, yet much of the design data for equipment used by pressure-suited astronauts is presently obtained from full-gravity ground tests.

The water-immersion tests were made in a swimming pool approximately 11 feet deep. A transparent test model of an airlock 4 feet in diameter and 6 feet long with hatch doors at each end was used to provide simulation of ingress-egress performance. (See fig. 3.)

During the water-immersion tests the subject was balanced to neutral buoyancy and stabilized in pitch and roll. A scuba-equipped safety man accompanied the test subject during each experiment.

A complete photographic record of the subject's maneuvers was made by an immersed 16-millimeter camera positioned normal to the airlock. A standard frame rate of 24 frames per second was used in all tests. An optical grid positioned behind the airlock and dimensioned markings 2 feet apart on the outside of the airlock test model were used in conjunction with the motion pictures to measure velocities of the test subject, time to perform specific tasks and subtasks, and body position. The dimensioned markings but not the optical grid were used also in the ground and aircraft tests.

DISCUSSION

A comparison of tests performed on the ground, aboard a zero-gravity aircraft, and by water immersion was provided from the motion pictures of the subject undergoing the tests. The discussion that follows is based on these film sequences (Langley Research Center film No. L-879).

For the ground tests, the subject performed various tasks at full gravity in the same transparent model of a space-vehicle airlock previously described. The tasks assigned may simulate those of an astronaut working in an artificial-gravity field aboard a space vehicle. The subject had difficulty in moving his hands and knees with $3\frac{1}{2}$ pounds of pressure in the suit. In one task he was required to pass over a 6-inch ledge to enter the airlock through the hatch and found it necessary to perform a pushup to get his legs over the ledge; even then, he scraped the legs of the suit. Forward motion on the hands and knees required considerable effort. Because the pressure tends to straighten out the knees of the suit, the subject reported that he had the feeling that he was going to be thrown on his face if he relaxed. A turnaround in the cylindrical airlock was obviously a strenuous maneuver. Fifteen minutes of operation on the ground tired the subject more than a similar period working under the water.

The subject also used the same airlock model to perform a similar set of maneuvers aboard the C-131 airplane at Wright-Patterson Air Force Base during zero-gravity trajectories. Because of the short duration of each trajectory, the ingress-egress tests were broken down into six test sequences. The subject showed greater incentive in these tests to move rapidly to avoid being draped over a sharp edge on the $2\frac{1}{2}$g pullout. During the pullout at this acceleration he lay on his side. He appeared to have some difficulty in making a turnaround during another trajectory. He was sometimes unable to complete this maneuver in the allotted time.

In the tests performed under water, before the maneuvers are attempted the subject is balanced to neutral buoyancy and neutral in pitch and roll. In the sequences showing the subject making a passage through the same airlock underwater, he tended to move forward in an inclined position in order to maintain forward vision through the helmet, as illustrated in figure 4. Motion through the water appeared almost effortless in these tests. The subject in making an exit through the hatch eases his grip on turning around and floats off in the water. This maneuver illustrates the necessity of tethering an astronaut to the exterior of the vehicle. The subject's ability to swim is very poor in the pressurized suit. In one test, the subject attempted to apply torque on a hatch handle which was tightened, but his body turned instead of the hatch handle.

In another assignment, the subject, in making an exit, caught one of his suit straps on the hatch. In this test, the safety man had to rescue him, since he was not capable of loosening himself in the pressurized suit. This limitation on maneuverability might have serious consequences in a space vehicle, since it is conceivable that the entire vehicle might have to be depressurized in order to perform a rescue on the outside hatch of an airlock. Once, when the subject was attempting an egress maneuver without the use of motion aids, he tried, in desperation, to use the hatch to control his body position. Because the hatch was not fixed he had only partial control of his body position.

The hands are not the only useful part of the body for the suited astronaut. The subject in one test learned to use his feet to execute a turnaround on exit. In the weightless environment of space the astronauts will quickly learn to perform acrobatic maneuvers, because such maneuvers are not limited by gravity and the movements need not be rapid.

A turnaround executed by the subject with the use of an interior handhold indicated that such handholds gave him only slightly more control than he could normally get by bracing himself between two surfaces, as shown in figure 5. On two occasions, the subject damaged the helmet or faceplate of the suit in performing a turnaround. In one test the subject made use of a handrail on exit from the airlock. In this maneuver, the subject appeared to have excellent control over his body position; he was able to maneuver with relatively little effort and in some cases could change his attitude merely by the use of his wrists. Hand rails on the exterior of a space vehicle will permit easily controlled physical positions and postural attitude of the crewmen during extravehicular task performance.

A test was made to demonstrate the use of a safety tether line during egress. The line is fastened to the end of the airlock and the subject shoves off. The line was drawn between his legs when he attempted to reel back; then he worked himself into such an awkward position that he almost smashed his helmet into the side of the airlock, but he was able finally to maneuver himself out of this position without help. This test showed that it is possible to attain a dangerous velocity and attitude on reeling in.

A task that the subject performed successfully was that of fastening his safety line on an eye on the exterior of the lock.

One assignment given the subject was that of examining the workspace limitations and his ability to reach control points. This problem was studied by requiring the subject to insert a phone jack in various locations on the inside of the airlock. By this means, workspace limitations, task allocation times, work cycles, and control locations can be established. During the water-immersion tests the subject was able to reach all positions within the airlock model, but during similar ground tests he was not able to reach some of the overhead positions.

EVALUATION OF TECHNIQUE

The validity, advantages, and disadvantages of the water-immersion technique will be discussed briefly. Figure 6 presents a plot of the maximum and minimum whole-body drag as a function of velocity as observed from the subject's performance of ingress-egress maneuvers similar to those just discussed. During these maneuvers the average velocity was about 0.5 foot per second, with the maximum seldom exceeding 1.3 to 1.8 feet per second. Subjective comments indicated that the forces necessary to overcome the resistance of the pressure suit were much greater than those required to overcome the drag of the water. When the velocities are low, this technique appears to be suitable for evaluating astronaut capabilities.

The advantages of the water-immersion simulation are its simplicity, relatively low cost, the ability to work in six degrees of freedom, and the additional time available to conduct detailed studies.

The results of the present ingress-egress studies can be summarized according to the following categories:

(1) Astronaut capability: The water-immersion simulation technique has been shown to be a useful tool in studying the capabilities of the pressure-suited astronaut under conditions of weightlessness. The test subjects were able to perform most ingress-egress tasks with relative ease and to develop quickly new skills and procedures.

(2) Spacecraft configurations and sizes: The airlock used in these simulations was 48 inches in diameter, which was marginal for turnaround by the pressure-suited subject, who was 5 feet 10 inches tall. Measurements from the photographs of the 6-foot-long airlock showed that a turnaround could be executed within a length of $4\frac{1}{2}$ feet, which would leave sufficient space for an inward opening hatch. This type of hatch offered few problems to the subject if it could be opened 90°. Substantial structural weight savings and reduced latching complexity are possible on airlock systems if hatches can be opened inward and seated with pressure. The 32-inch-diameter circular hatch was sufficiently large for easy passage of the subject in the weightless state and did not begin to pose a problem with this pressure suit until the diameter was reduced to less than 26 inches. The outward opening hatch was often in the way for maneuvers on the exterior of the airlock.

(3) Handholds, handrails, and motion aids: The experiments have shown that handholds are not advantageous in confined spaces where traction can be attained by other means. Protrusions in a confined space are a definite hazard from the standpoint of entanglement with the suit straps and damage to the helmet. However, handholds on the exterior are a necessity, since no other means of traction are available. Handrails are advantageous for easy locomotion and for controlling body attitude. It is conceivable that handrails could be a most desirable motion aid to frequently visited locations on the exterior of a space vehicle. For torque application, hand or foot braces are a necessity if body orientation is to be maintained.

(4) Tether lines: Experiments with the safety tether line have shown that the subject is able to reel himself back to the attachment location; however, he has no axial control of attitude perpendicular to the tether. In the present studies the line was considered only as a safety device to prevent loss of the astronaut. Total simulation of the dynamics of a tethered astronaut is not possible with this technique because of the damping effects of the water; however, comparison of these tests with recent flight experiments shows considerable similarity in attitude control and the capability of the astronaut to recover on a short safety line. Cargo transfer by the astronaut on a tether line appears to be a real problem and requires further study.

(5) Workspace limitations: The study of workspace limitations indicated that working in a confined space in the weightless state is less of a problem than anticipated. The location of controls in an airlock can be determined by similar tests. Working with pressurized gloves requires handles of at least 1-inch diameter to provide the necessary feel and dexterity.

(6) Operational procedures: It is apparent from these studies that many operational procedures can be developed by the water-immersion simulation technique. During the early experiments the subjects made little or no use of their legs or feet; however, they quickly learned to perform maneuvers with their feet and to brace themselves with their legs in applying torque.

This continuing experimental program shows promise of providing a better understanding of human factors and capabilities in extravehicular operations; it contributes data applicable to future configurations, to manipulation and control devices and safety-design features for airlock systems, and to other extravehicular equipment for advanced manned space vehicles.

CONCLUDING REMARKS

A technique has been developed and validated wherein a pressure-suited subject is immersed in water and maintained in a neutrally buoyant condition to simulate the external tractionless characteristics of the zero-gravity environment in six degrees of freedom.

The water-immersion technique can be applied in many current and future studies of extravehicular space missions and tasks, such as the ingress or egress through airlocks, evaluation of the astronaut's extravehicular work capabilities, development of procedures for crew and cargo transfer techniques, and provision of design data for future vehicles and related equipment.

Similar experiments performed by water immersion and from zero-gravity aircraft flights have shown that the water-immersion and aircraft tests are comparable when the velocities are low. The two simulation techniques are complementary and information from each should supplement that from the other to increase understanding of the overall problem.

ASTRONAUT EGRESS

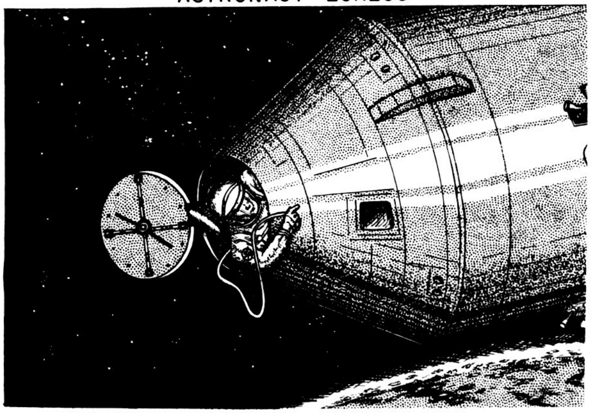

Figure 1

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SUIT PRESSURIZATION AND BREATHING SYSTEM

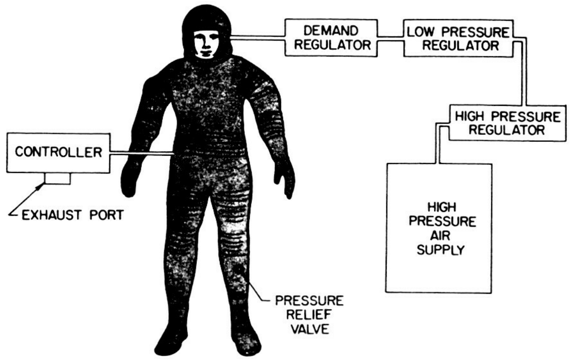

Figure 2

MODEL AIRLOCK WITH SUITED SUBJECT

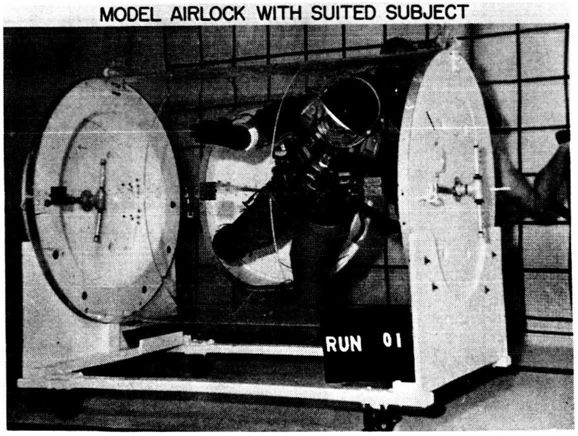

Figure 3

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SUBJECT MAKING INGRESS

Figure 4

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SUBJECT PERFORMING TURNAROUND

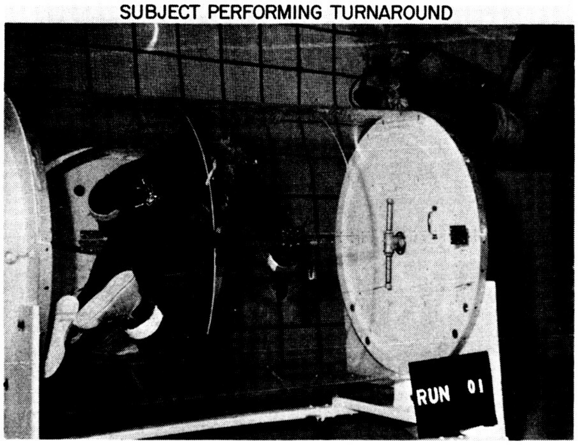

Figure 5

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WHOLE-BODY DRAG PLOTTED AGAINST VELOCITY

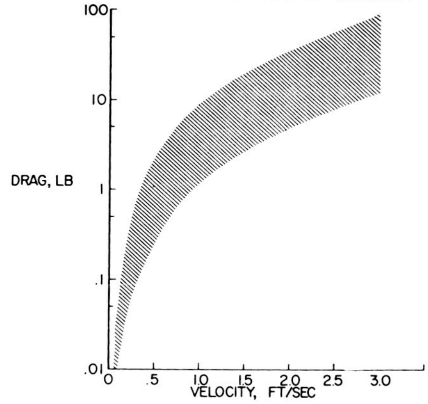

Figure 6