NASA CONTRACTOR REPORT

NASA CR-859

NASA CR-859

STUDY OF ASTRONAUT CAPABILITIES TO PERFORM EXTRAVEHICULAR MAINTENANCE AND ASSEMBLY FUNCTIONS IN WEIGHTLESS CONDITIONS

by E. C. Wortz, L. E. Browne, W. H. Shreck, A. J. Macek, W. G. Robertson, and M. R. Gafvert

Prepared by
AIRESEARCH MANUFACTURING COMPANY
Los Angeles, Calif.
for Langley Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • SEPTEMBER 1967

NASA-CR-859

STUDY OF ASTRONAUT CAPABILITIES TO PERFORM EXTRAVEHICULAR MAINTENANCE AND ASSEMBLY FUNCTIONS IN WEIGHTLESS CONDITIONS

By E. C. Wortz, L. E. Browne, W. H. Shreck, A. J. Macek, W. G. Robertson, and M. R. Gafvert

Prepared under Contract No. NAS 1-5875 by
AIRESEARCH MANUFACTURING COMPANY
A Division of The Garrett Corporation
Los Angeles, Calif.

for Langley Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

ABSTRACT

Experiments were conducted on man's capabilities to perform manual work in the weightless environment. More than 200 experimental conditions were studied. The independent variables were simulation techniques, tasks, locomotion aids, restraint devices and tools. This document describes the final results of both the analytical and experimental studies. Conclusions are drawn with respect to the effects of the independent variables, the human engineering observation, quantitative analyses and physiological parameters. Hypotheses are advanced concerning the improvement of work in the weightless environment.

FOREWORD

This report was prepared in the Department of Life Sciences, AiResearch Manufacturing Company, Los Angeles, California. The technical assistance of N. J. Belton, D. Bunch, R. A Diat, L. J. Miller, L. J. McLean, and G. Raynes is gratefully acknowledged.

CONTENTS

CONTENTS (Continued)

ILLUSTRATIONS

a

TABLES

STUDY OF ASTRONAUT CAPABILITIES TO PERFORM EXTRAVEHICULAR MAINTENANCE AND ASSEMBLY FUNCTIONS IN WEIGHTLESS CONDITIONS

By E. C. Wortz, Ph.D., L. E. Browne,
W. H. Shreck, A. J. Macek, Ph.D.,
W. G. Robertson, Ph.D., and M. R. Gafvert
Department of Life Sciences
AiResearch Manufacturing Company
A Division of The Garrett Corporation

SUMMARY

The performance of this program, under Contract NAS 1-5875, was marked by several major milestones. These were the construction of a test facility designed specifically to achieve the objectives of the program, the completion of analytical studies related to underwater drag, and the conduction of an extensive series of exploratory tests designed to ascertain the effects of weightless conditions on man's capabilities to perform manual maintenance and assembly functions.

This report describes in detail the apparatus, methods, procedures, and observations made during the program. Essentially, two simulation techniques were employed in addition to baseline studies at one-g: (1) a six-degrees-of-freedom simulator and (2) neutral buoyancy. Other indpendent variables were the type of task, locomotion aids, restraint devices, and tools. Dependent variables, used for the evaluation of the effects of the independent variables, were problems in task completion, errors, task times, and physiological parameters which included metabolic rate data. Since one of the simulation techniques involved water immersion, a study was conducted to ascertain its effect on the dependent variables. As a result of the study, "dry diving" was selected over wet diving since the former is less likely to produce spurious physiological data than the latter. Other studies were conducted on the possible effects of drag on performance while using the neutral buoyancy simulation technique. A formal report, "Mathematical Model Analysis of Underwater Simulation (LS-66-0794)," was submitted which provided a detailed plan for the continuous on-line computation of drag energies for the purpose of both ascertaining the fidelity of the simulation and the correction of metabolic data.

A fourth major analytical effort undertaken was the development of a "task taxonomy" for the purpose of organizing the data such that general principles of extravehicular activity (EVA) could be evolved. This taxonomic tool is described together with examples of its application in the section on Quantitative Results.

The results of these extensive experiments (more than 200 distinct test configurations) are described in the sections on Human Engineering Observations, Quantitative Results, and Physiological Results. Due to the extent of the data analysis achieved in this program, each of these three sections includes lists of the numerous conclusions and hypotheses which may be drawn.

INTRODUCTION

This document represents the final report of the program "Study of Astronaut Capabilities to Perform Extravehicular Maintenance and Assembly Functions in Weightless Conditions." This study was conducted for NASA/ Langley Research Center under Contract NAS 1-5875. The program was composed of a series of analytical and experimental efforts that are described in the following sections of this report. The methods, procedures, and apparatus used during the program are also described. Conclusions are drawn about the various aspects of EVA such as the effects of tools, restraint devices, locomotion aids, and other aspects of EVA work.

NASA is currently planning extended duration space missions during which extravehicular operations will be required. Extravehicular operations will permit the performance of tasks such as maintenance and repair of equipment, assembly of large equipment, and assembly of modular units. In order to better understand the capabilities, limitations, and level of performance of the astronaut in performing these extravehicular tasks and to develop techniques and equipment for accomplishing them prior to flight dates, it is necessary to conduct simulation studies. This program is unique in that it provides for the assessment of EVA work by several techniques of simulation. Since no single technique provides full fidelity, the comparison of tasks among simulation techniques improves the confidence in the generalization of "earthbound simulation data" to the space situation.

Another very unique feature of this particular program is its breadth. In the search for unifying mechanisms and principles, more than 200 unique test configurations were explored. This approach was necessary in order to "shred out" relevant problem areas so that future research could be appropriately structured. Consequently, in this very basic attempt to structure the problem of EVA work, the research was limited to the most primitive form of accomplishing work--manual labor. Such an examination both provides the fundamentals for understanding any man-machine interface in the weightless environment and permits the collection of data appropriate for the proper man-machine functions allocation for weightless work at the most basic level. The most lightweight system for providing human directed maintenance and assembly is the unaided man. Obviously, the EVA worker will need work aids; however, all space endeavors need to consider the penalties associated with weight, volume, and power. Understanding man's manual EVA abilities will allow the development of truly optimized systems of men, tools, and machines for the conquest of space.

The scope of the study included a theoretical and engineering research program to determine the capabilities and limitations of the astronauts in performing extravehicular maintenance and assembly tasks not requiring external guidance propulsion or power assist under zero gravity conditions. All services, materials, facilities, and test subjects to perform the combined theoretical and experimental study were provided.

The theoretical study, which was used as a basis for planning and performing the experimental study, included:

a. An analysis of the drag and damping effects on the test subjects and equipment to be used in the water immersion simulation.

b. The development of suitable modeling and scaling laws to define the relationships between the experimental simulation and the zero gravity conditions of space.

c. An analysis of the types of extravehicular maintenance and assembly tasks which can be suitably studied by this means of sirnulation.

d. Evaluation of techniques of instrumenting water immersion simulation.

e. Development of techniques for analysis of data.

On the basis of the results of the theoretical study, an experimental study of extravehicular astronaut maintenance and assembly techniques for the purpose of defining the capabilities and limitations of the pressure= suited astronaut was performed, during which tasks offering particular problems were examined, solutions to particular problems were worked out, and those task areas where additional research could profitably be performed at a later date were defined. Also during the experimental study phase the following were accomplished.

a. A detailed test plan of the approach for accomplishing the maintenance and assembly tasks was prepared and submitted.

b. An engineering program was planned and executed that could suitably be performed by water immersion and other techniques.

c. Additional hardware and test equipment was designed and constructed. (Hardware and test models used in this program were not elaborate, were constructed of commercially available parts where practical, and were designed to demonstrate economically the basic principles associated with problems involved in extravehicular erection and maintenance.)

d. Comparative tests of several maintenance tasks were conducted on the ground under full gravity conditions to examine the differences during weightless performance. The data recording and analysis methods were compatible, and comparison of data from the different simulation methods was made on a common basis.

e. Comparative tests to evaluate the water immersion simulation by using other means of simulation for conducting tasks were conducted.

f. An analysis of the data collected during the tests was performed.

The following sections of this report describe in detail the analytical studies, the methods and procedures used in the experimentation, the experimental design, and the results and conclusions of the experiments. The results are given in three sections: Human Engineering Observations, Quantitative Results, and physiological Results.

SECTION I

ANALYTIC STUDIES

Before the empirical tests began, the following analytic studies were conducted on the problems associated with using neutral buoyancy simulation in studying the problems of work under weightless conditions.

a. A study of the physiological effects of diving

b. A behavioral study to arrive at a task classification system that might be used in EVA research

c. A development of a mathematical model for computing the energy loss associated with underwater drag

d. Development of a verification plan for the mathematical model and a plan for continuous on-line generation of drag energy data during the simulation experiments

THE STUDY OF DIVING PHYSIOLOGY

Since a portion of this program is concerned with physiological measures--e.g., metabolic rate--it was felt necessary to review some of the effects of submersion and hyperbaric pressures in human physiology. The effects of submersion on human physiology are thought to be in part psychologically induced. Consequently, the effects of submersion might be induced even when wearing a pressurized suit filled with air. These submersion effects include conservation of oxygen by "increase in oxygen debt."

Studies of underwater physiology have been approached from several quite different points of view. Some investigations have been concerned with the effects of immersion only. Others have been concerned with short periods of activity in shallow water. Still others have emphasized the study of short and moderately long activity at great depths. Recently, experiments such as those by the Sea-Lab, Link, and Costeau groups have emphasized investigation of a wide 'range of activity at great depths for prolonged periods.

The results of experiments on immersion and diving in shallow water hold primary interest for the present study. For this reason, information about the physiology of diving at great depths will not be emphasized.

The majority of immersion studies have involved minimal or no activity by the subjects and, in fact, have been termed studies of "hypodynamic states." these kinds of experiments have shown that prolonged immersion in water (2 to 7 days or more) induces significant changes in circulation, muscle, and metabolism in general. Some of the phenomena observed during immersion may be listed as follows:

a. Redistribution of body fluids

b. Orthostatic hypotension

c. Decreased demands for musculoskeletal activity

d. Decreased metabolic rate

e. Cardiodynamic activities characteristic of recumbency

Gravelins and Barnard (ref. 1) claim that evidence of cardiovascular deterioration is readily apparent after 6-hr immersion. Graybiel and Clark (ref. 2) observed orthostatic hypotension within four hours.

When a subject is tilted after immersion he will usually develop an orthostatic tachycardia and an increased diastolic pressure. This suggests that reflex vasoconstriction is not impaired. Urinary norepinephrine is usually decreased during immersion, however, and it has been suggested that this reflects decreased vasomotor activity. Nevertheless, the precise role of the autonomic nervous system in the deconditioning of immersion remains undetermined.

Many subjects show an "imnersion diuresis" or free-water clearance. This is also incompletely understood. It has been hypothesized that this is due, in part, to reflex inhibition of antidiuretic hormone by blood volume stimulation of atrial volume receptors. The evidence for this hypothesis is that ADH injection or positive pressure breathing (15 mm Hg) prevents the diuresis, and the plasma volume initially increases. However, this evidence is still insufficient to separate volume receptor mechanisms from altered renal hemodynamics.

Finally, metabolic changes reflected in urinary nitrogen, blood composition, and immunochemical reactions are even more difficult to explain; however, they also appear to result primarily from immobility and passivity, for they have been observed in bed rest as well as immersion studies.

The number of studies on dividing animals far exceeds those on diving man, but certain patterns emerge from the animal work which are applicable to man. Diving reptiles, birds, and mammals can sustain themselves underwater for comparatively long periods by decreasing their metabolism. There is evidence that blood flow to muscle and skin is drastically reduced during submersion.

Peterson (ref, 3) has summarized the evidence for redistribution of blood flow and the attendant metabolic changes that occur during submersion. Some of these may be listed as follows:

a. Incisions into skin and muscle do not bleed.

b. Increased lactic acid appears in the blood after ascent (suggesting that it is trapped and noncirculating during dive).

c. Myoglobin O_2 is practically depleted while blood remains almost 50 percent saturated.

d. Direct arterial pressure recordings indicate an increased peripheral resistance; i.e., the rate of pressure fall during diastole is decreased.

Man also shows a redistribution of blood flow and an increase in lactic acid concentration as a diving response. Further, he shares with other animals, in varying degrees, apnea, bradycardia, and a sudden tachycardia on emergence (in most cases). Diving responses are complicated by the fact that they can be elicited by many stimuli, e.g., loud noise, certain postures, immersion of the whole body, and breath holding. Surprisingly, one of the few stimuli that does not produce diving responses is application of pressure in a diving chamber, which is representative of an air-filled suit.

Apnea-bradycardia is usually of sinus origin and appears to be a reflex, because of the rapidity of its onset. The heart rate may decrease to 50 percent of the surface rate under these conditions. The onset and degree of the bradycardia appear equally pronounced in good and poor swimmers and persists in spite of vigorous exercise under water. This was the first reported by Irving (ref. 4) and confirmed by Scholander and Olsen (ref. 5), but contradicted by Craig (ref. 6). It should be noted, however, that Craig used one subject who breathed 100 percent O_2 for 5 min prior to descent and that he did but one experiment with this subject. Irving observed that just submerging the face was an adequate stimulus for a bradycardia which is of longer duration than that often seen during breath holding in air. Wolf (ref. 7) noted the expected fact that this bradycardia may be easily modified by stress, fright, or harassment.

Scholander (ref. 8) observed extrasystoles during the dive and atrial fibrillation during the recovery phase. Olsen (ref. 9) reported that the most consistent changes in diving man were sinus bradycardia and sinus arrythmia, but he also observed (1) sinus arrest with subsequent nodal or ventricular escape; (2) A-V block, A-V nodal rhythm, and idioventricular rhythm; and (3) alteration in configuration and amplitude of the P-wave (which generally decreased) and the T-wave (which became peaked and elevated). Several investigators feel that if a subject's heart fails to slaw during simple immersion, it is a good indication of physiologic and/or psychologic unsuitability for underwater work.

In animals, systolic pressure is maintained or elevated during a dive. During this time there is an associated prolonged fall in diastolic pressure. The picture is not so clear in humans. For example, Olsen measured brachial arterial pressure directly (subject submerged with arm out of water) and noted that systolic pressure rose within the first 10 sec and remained elevated until the end of a dive. Examination of his data does not permit an unqualified statement about changes in diastolic pressure. On the other hand, Scholander measured brachial arterial pressure using a cuff technique (subject submerged with arm out of water) and reported no significant change in systolic or diastolic pressure during diving.

It was mentioned earlier that redistribution of blood flow occurs during diving. One indication of apparent shunting of blood past muscles was suggested by the failure of blood lactic acid to increase coincident with marked increase in muscle lactate. This phenomenon has been observed in a variety of animals. Similar changes have been noted in scuba divers who were able to do apneic diving for as long as 3 min at rest and 1.5 min with exercise. Consequently, it has been postulated that there is decreased blood flow to muscles in diving humans. The delay in appearance of lactic acid in blood complicates this idea for man, however, because there is also a delay following surface swimming and sprinting and because man's submergence time is relatively short

It must be kept in mind that although blood flow through contracted muscle is decreased and bradycardia is usually associated with severe asphyxia, many other factors associated with diving affect the cardiovascular system.

In summary, the study of the literature showed three classes of effects from diving: (1) those resulting from pressure, (2) those resulting from getting wet, (3) and those resulting from being submerged. The literature does not systematically distinguish between the results of being submerged that come from being wet vs those that come from the subject's knowledge that he is underwater. It is known, however, that pressure alone does not produce the physiological syndrome of "diving responses" and that getting the face wet without submerging produces many symptoms in this syndrome. In view of this knowledge, the dry diving technique was chosen as the one least likely to produce spurious data.

TASK TAXONOMY STUDY

The purpose of the task taxonomy development study was to begin early to provide a structure for analyzing the data, planning future experiments, setting up tasks, and for ordering those activities which could be simulated adequately underwater and those which could not. It was apparent at the outset that each of the many possible applications of a work classification system could result in systems of different forms. The decision was made by the analyst to try setting up a comprehensive method of classifying weightless work and then modifying that system in the light of the specific inadequacies that would appear as attempts were made to apply it to the organization of the data.

In developing a system of classifying the activities involved in weightless work, the analyst worked with past classification attempts extensively. The publications of L. M. Stolurow (ref. 10), A. W. Melton (ref. 11),

K. U. Smith (ref. 12), E. A. Fleishman (ref. 13 through 17), and Rudolf Laban (ref. 18), and the area of time and motion analysis were studied.

The work of Stolurow was largely discarded because the emphasis on cognition in his categorization left it largely irrelevant to the problems of weightless work. After task classification proves useful in space, however, Stolurow's early work in the critical cognitive characteristics of a task may well become important in such IVA and EVA maintenance jobs as fault isolation.

Melton's method of labeling and classifying tasks turned out to to be not ambitious enough to satisfy the need for an EVA task taxonomy. His classifications, such as "procedural, closed loop, and verbal," are useful in working through the transition between the everyday task taxonomies, which are used by most people studying human performance, and the more formal task taxonomies that ought to be developed.

Smith's work, with his peculiar structure of human performance into types of control and feedback loops, looked promising at first, but the analyst finally decided that while control loops and feedback mechanisms are critical, working with them would be cutting the problem too fine for a first attempt. The results of the present study indicate problems in feedback--such as those associated with EVA gloves and restricted vision--which will probably be understood and classified partly with the help of the research of K. U. Smith.

The work of Rudolf Laban in ballet and dance notation led him to be interested in studying human effort in production lines and general assembly work. His classification scheme is the most ambitious of all attempts, laying all motions of effort in a three-dimensional scheme of force, control, and speed of motion. He then worked with the various parts of the body concerned with each motion. His approach was not pursued because it was too comprehensive. Using a space adaptation of Laban's methods, a human factors analyst could classify all the work done in the studies described in this report. There are two problems: some meaningful distinctions would be omitted, and many cells in Laban's complicated n-dimensional matrix would not be filled. The structure would be more difficult than the classification problem. In future iterations of the task taxonomy, however, Laban's dimensions of force, control, and speed will most likely be incorporated as the most promising way of describing the force and dexterity required to do a job.

The most active psychologist in recent years in the area of task taxonomy is E. A. Fleishman. Fleishman's work is empirical in contrast to Laban's logical-theoretical structuring. One advantage of the empirical approach to task classification is that many cells of the description that might be included theoretically do not arise in practice. For example, Figure 1-1 shows a set of categories of physical exercise derived by Fleishman in a study of physical fitness. Laban's

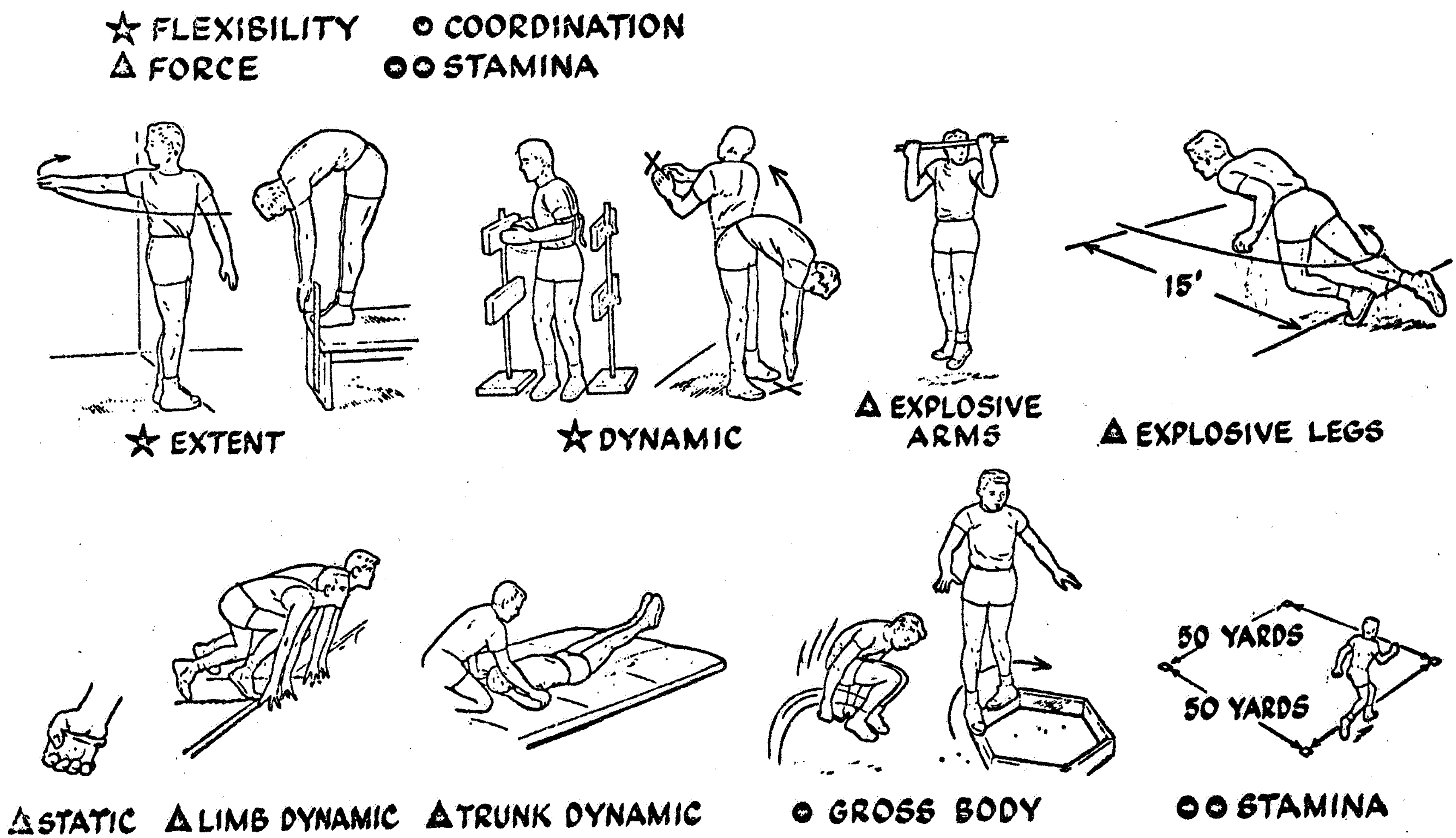


Figure 1-1. Fleishman's Categories of Physical Exercise

dimensions of force, dexterity, and speed are visible in the categories, but not completely. As an example, Fleishman's empirical category of explosive force is reminiscent of a joint classification by Laban of a task involving great force and speed. While Laban's system would have such a category for movement of the trunk, this category does not occur in the results of Fleishman's factor analytic study.

It is possible that human effort in space will ultimately be classified in a large matrix involving many dimensions such as type of feedback, amount of feedback, cognitive characteristics of the task, amount of speed and force, etc. It is quite definite, however, that such a matrix will also have to include task-oriented aspects such as those used by Taylor and Gilbreth in their early work in classifying tasks as a basis for their time and motion studies.

The final choice made for a task taxonomy for this program was a logic flow classification scheme. This scheme is seen in Figure 1-2. The logic flow classification is used in psychology in many situations. The methods for distinguishing among diagnostic categories of the mentally ill constitute a logic flow classification scheme. Based on early data obtained in the studies, the logic flow classification was revised to the form shown in Figure 1-3. The form will certainly be revised again. In comparing Figures 1-2 and 1-3, the most notable observation to be made is that Figure 1-3 is tending back toward a matrix type of classification system. For example, the blocks under managing a load are identical for three different categories. This is the start of a matrix involving the ways of handling a load and the degree of restraint and movement currently in effect for the astronaut. The matrix toward which the system is evolving is different from the ones suggested above.

The current system, as shown in Figure 1-3, was intended to be exhaustive enough to cover the work in the simulated performance of weightless tasks and to cover the work actually done in space thus far. It also meant to cover the work in planning for EVA tasks to be performed in space.

The logic flow system approach to classifying tasks is illustrated in Figures 1-4 and 1-8, which are taken from the task of assembling and erecting the inflatable module. Figure 1-4 shows the subject with a load in his left hand as he arrives at the end of a ladder type of locomotion aid and module erection boom. He is stationary with respect to the parent mass--in this case, the ladder--and he is not restrained. (Note the unattached restraint buckle to the left of his package.) Thus, he is free at his work station. The subject's task is not entirely clear from the photograph, but is known from the context. He is opening the package containing one piece of an inflatable module, which he is going to erect.

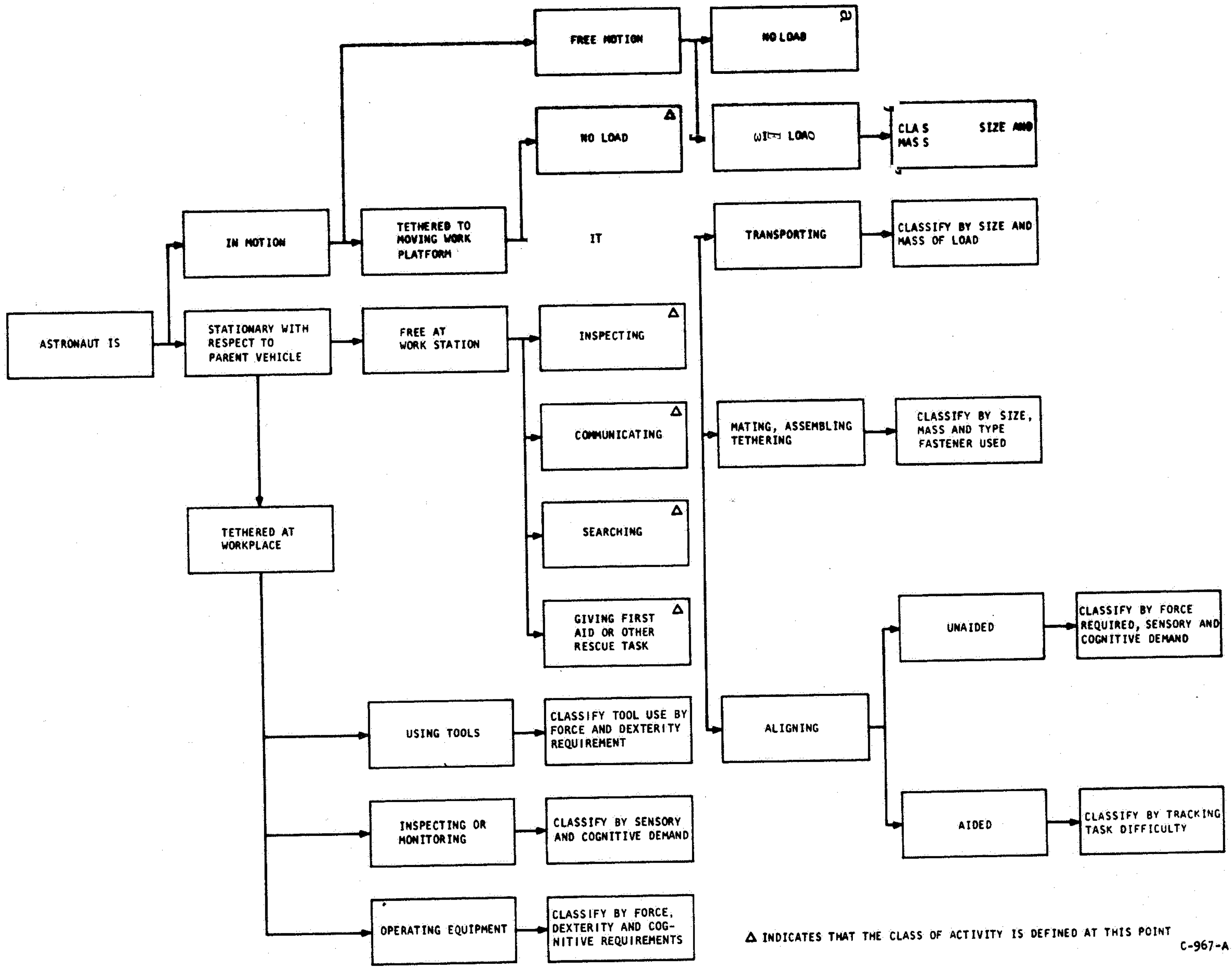


Figure I-2. EVA Classification Chart

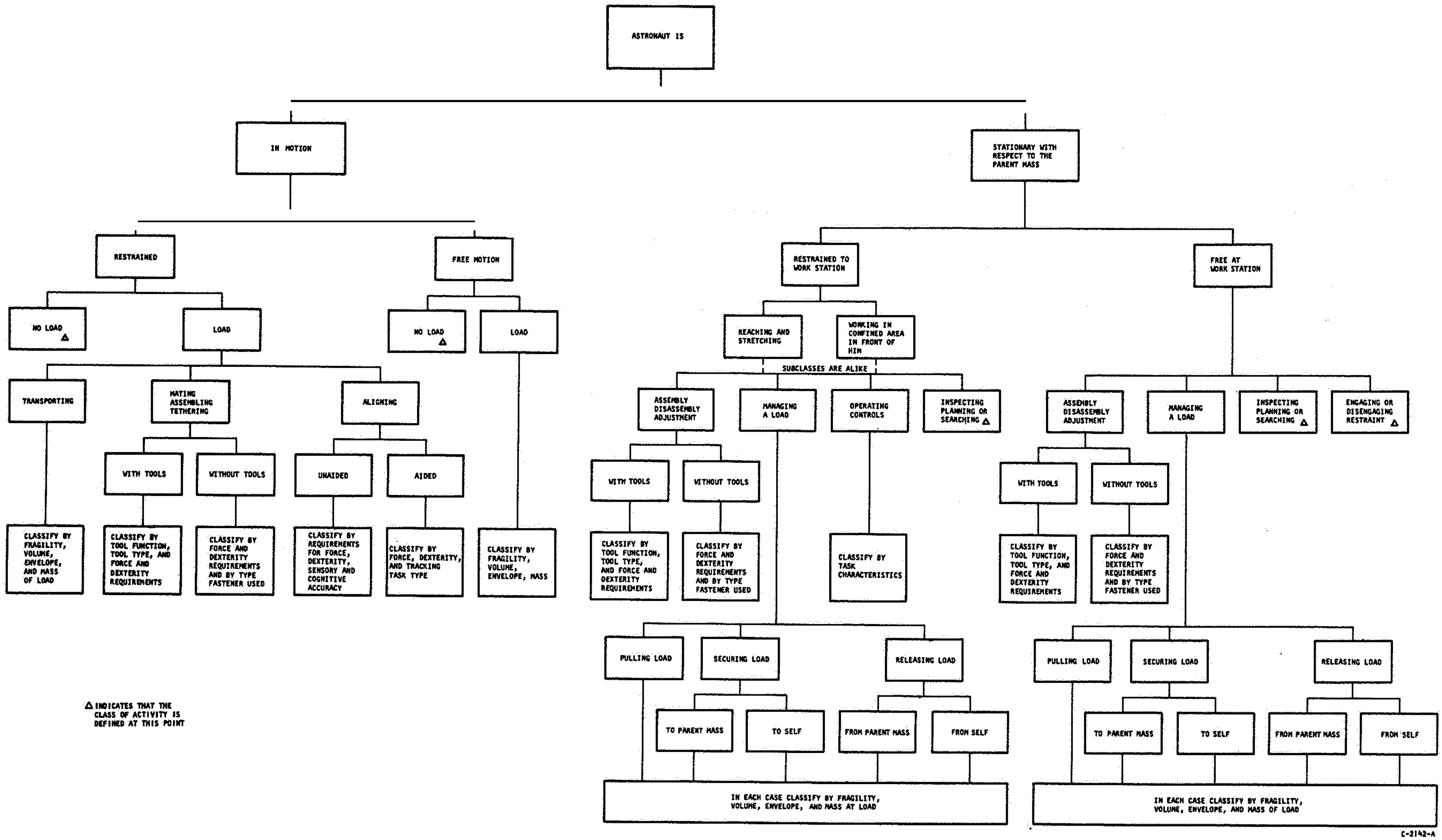
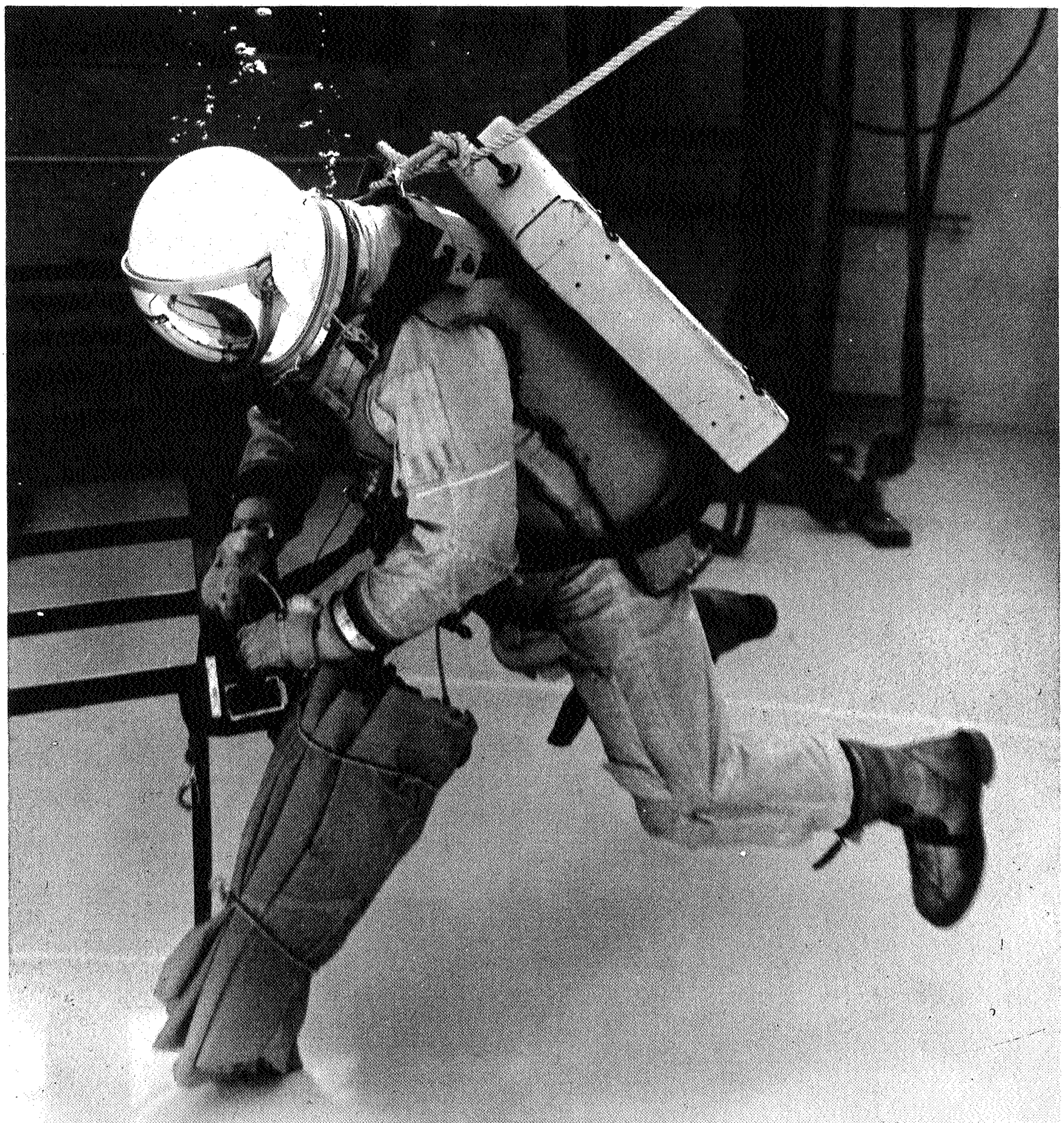


Figure I-3 Current EVA Classification Chart



59185-4

Figure 1-4. Example of Disassembly by a Subject Who Is Stationary and Not Restrained

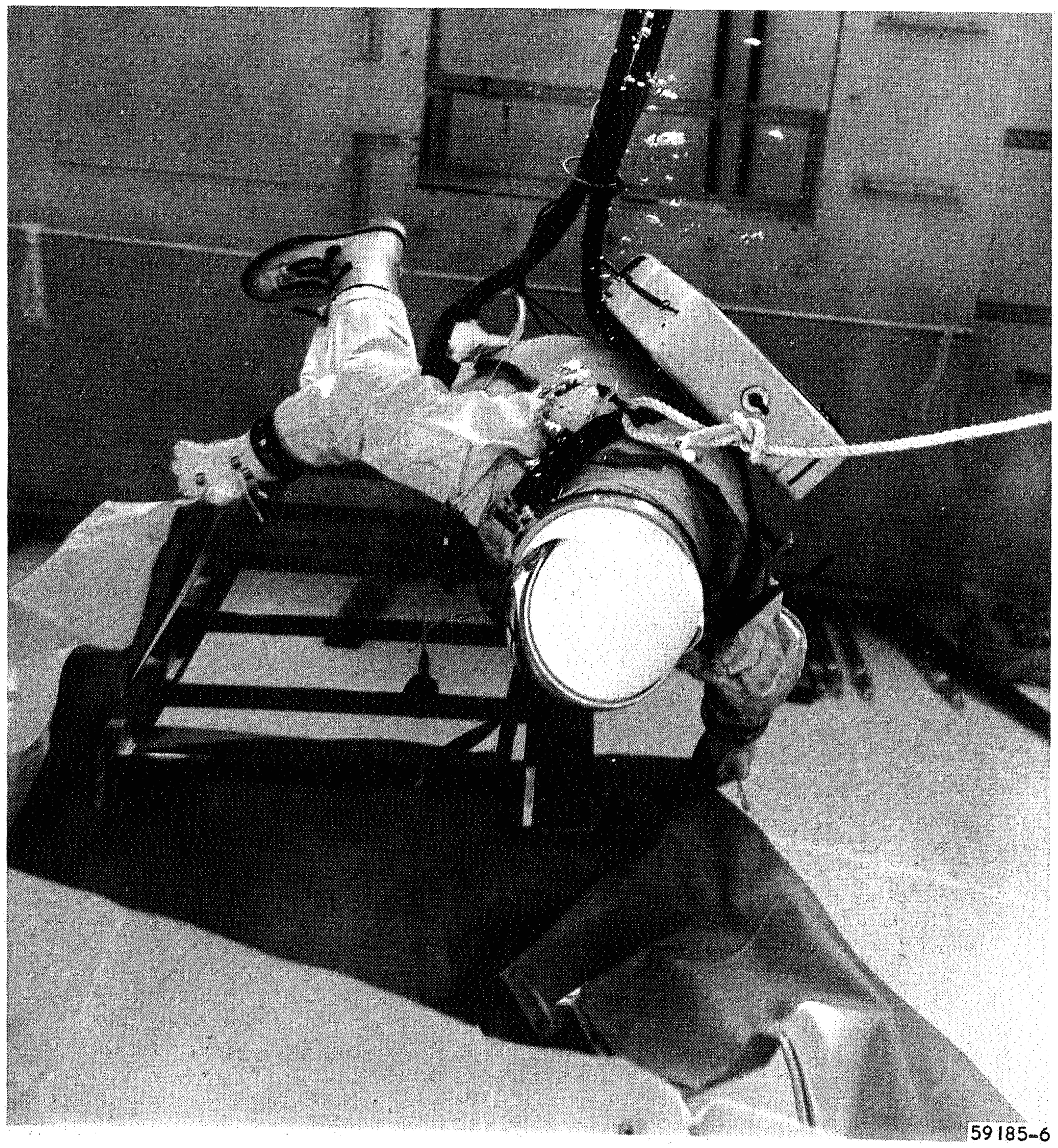


Figure 1-5. Example of Pulling a Load While Stretching and Reaching When Restrained to the Work Station and Stationary

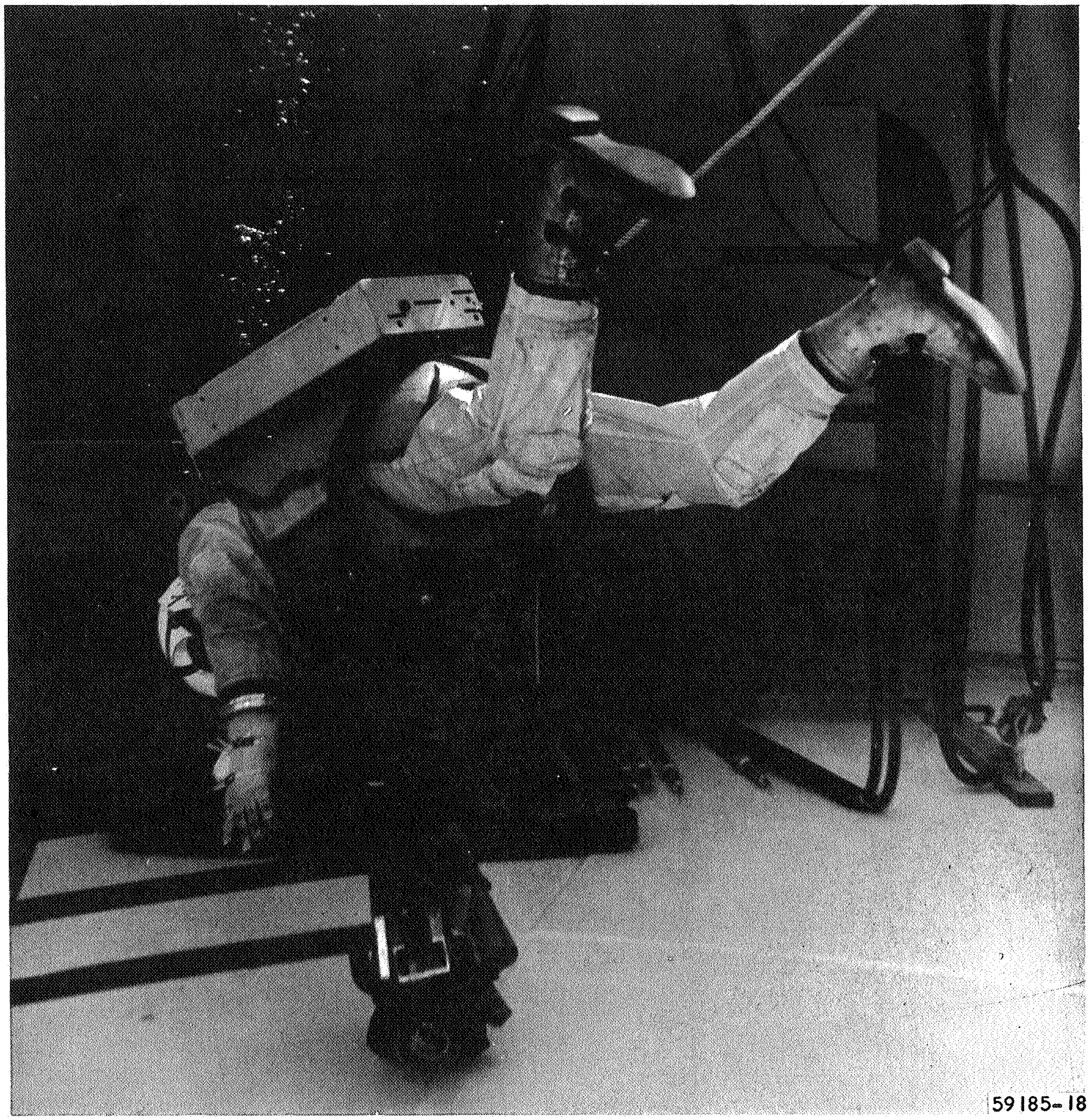


Figure 1-6. Example of Carrying a Load in Free Motion

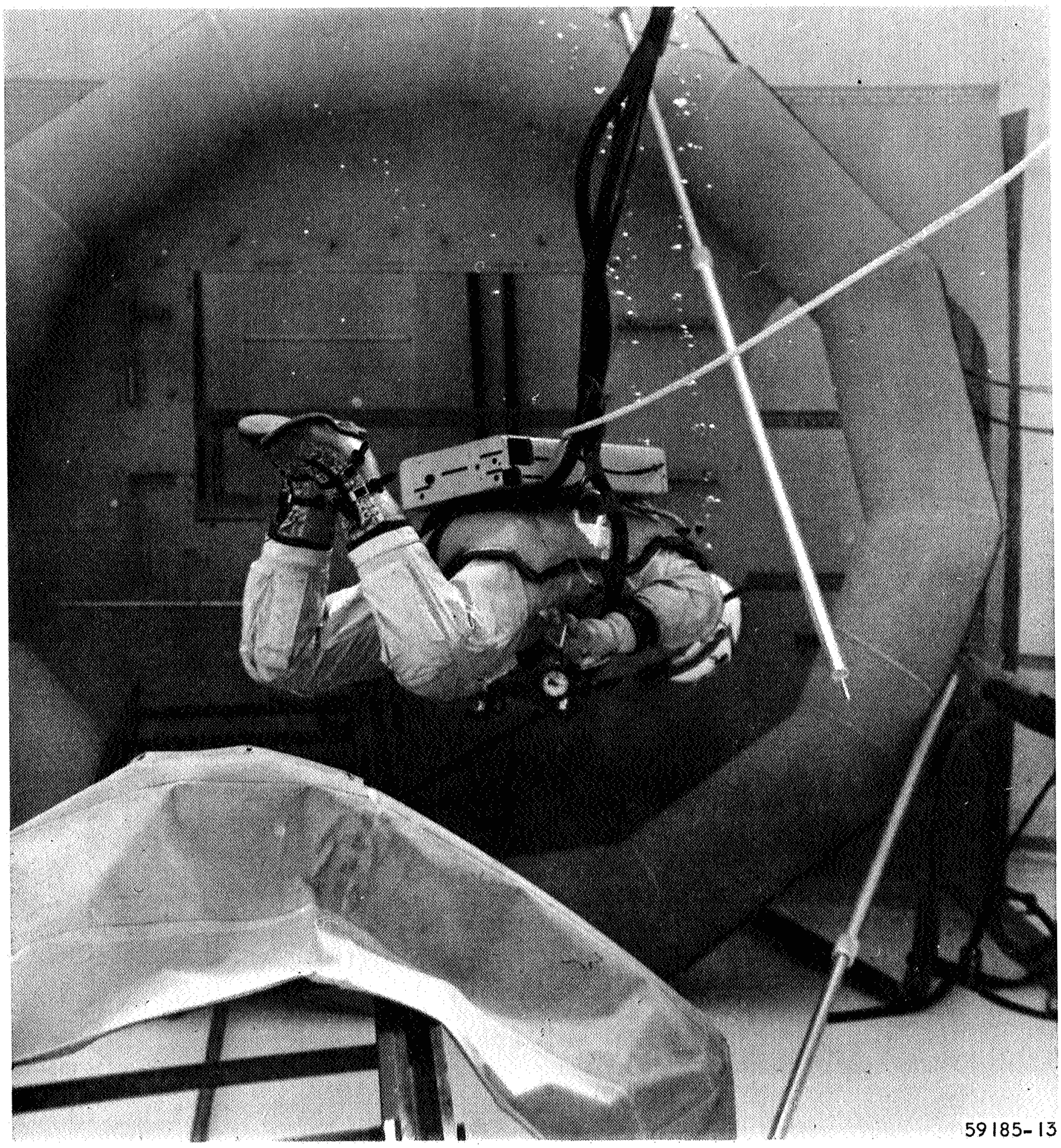


Figure 1-7. First of Two Photographs Exemplifying Line Straightening, a Task Not Covered in the Classification System Given in Figure 1-3

Figure 1-8. Second of Two Photographs Exemplifying Line Straightening, a Task Not Covered in the Classification System Given in Figure 1-3

This puts the task into the category of assembly, disassembly, and adjustment, and into the subcategory of this type of work without tools. Further classification would indicate that little force and considerable dexterity are required in this task. Note that the subject has a back-up safety tether and that his left hand holds him to the parent mass, holds the package in place, and holds part of the cord he is untying.

Figure 1-5 shows that the subject is (1) stationary with respect to the parent mass, (2) restrained to his work station — the restraint buckle is attached to the handle of the C-clamp, (3) in the act of reaching and stretching, (4) managing a load, (5) pulling that load, and (6) that the load is rugged, is not voluminous, has a large envelope, and has negligible mass. The classification of load fragility, volume, envelope, and mass will ultimately be strictly quantitative.

Figure 1-6 shows the last of the simple classification examples. the subject is in motion. The crab walk along the locomotion aid occurred frequently in this study. Having put the first module in place, he is bringing the second. The subject is in free motion and is carrying a load. Note that his restraint is attached to the package. In addition, he is holding the package with his right hand, which he slides along one side of the ladder type of locomotion aid while he pulls himself along with his left. The final step in the classification is to describe the load as being rugged and small with respect to volume, envelope, and mass.

Figures 1-7 and 1-8 present a classification problem. The act shown in these figures is a legitimate EVA that is not covered in the current classification scheme. The subject is working to straighten his lines. His umbilical and safety line became fouled and, following established test procedure, he straightened them. The method shown in the two figures seems unorthodox, but proved very effective. He leaves his single-strap restraint attached and spins around to straighten the lines. Figure 1-7 shows the subject in a spin; Figure 1-8 shows him slowing himself down during the last turn. The task of straightening lines and its various methods can easily be added to the current classification scheme. When this is done, the logic flow taxonomy will resemble a matrix type of taxonomy even more.

DEVELOPMENT OF THE MATHEMATICAL MODEL

The most evident simulation weakness in the water immersion technique lies in a simulation environment that is extremely viscous One possible effect of this difference between the situation underwater and that in space is that the metabolic rate of the subject working underwater will be composed of the energy required to get the work done in space and the energy required to overcome the drag effects of the water. Thus, one application of the mathematical model could be to assume that the effect just mentioned is the only water drag effect and to concentrate on correcting the observed metabolic rates. Under this application, the metabolic rates taken from subject's working underwater would be reduced by the amount of energy that would have been required to overcome the underwater drag effects in doing his work. Obviously, the effects of water damping are not that simple. Water drag, for example, will reduce the effort required by the subject to hold his pressure suit in a position opposing the tendency of the suit. It is also possible that the water's damping of the velocities imparted to a locomotion aid or in the motion of a subject would be helpful in that he would not have to expend as much energy to slow down or stop these velocities. Regardless of the detailed consequences of the damping effect of water, the anlysis given will be useful in delineating the extent of these damping effects.

Due to a steady loss of momentum to neighboring water layers, the damping forces imposed by the water upon the moving subject tend to constantly decelerate the motion. No energy is required in space to sustain a motion of uniform speed because there is virtually no retarding force; the same motion is possible in water only when additional energy is supplied. The scaling analysis thus involves the calculation of this additional energy expenditure for overcoming water drag. The value of drag energy can then be scaled off from the total energy expenditure to extrapolate zero-gravity, zero-ambient-drag situations.

To evaluate the drag force during underwater maneuvering, it is necessary to know the history of the positions and velocities of every segment of the pressure-suited subject. This is accomplished by employing accelerometer recordings of the segment joints of the body. Such methods of measurement makes it possible to determine not only the segment translations, but also pure rotations about the centroid of the segment. Because of the restraints imposed by the pressure suit and the concern for mission safety, EVA may well be limited to low speeds, which also limit the range of Reynolds numbers of underwater motions for programmed tasks.

In reference to drag calculations, the present state of the art can only investigate simple geometric shapes, such as ellipsoids, spheres, and cyclinders. Only by experiment will the calculations for complicated shapes be possible. For theoretical study, a mathematical model, made up of simple geometric shapes to represent the immersed body, seems to be the best approximation for determining the analytical drag values. Abundant information about the component shapes is available. This information was used in connection with the simple figure depicted in Figure I-9, to arrive at a method for determining the amount of energy needed to overcome the drag of the water.

When a completely immersed body is in motion relative to the water, it experiences a resistance which may be termed "viscous drag," since the resistance results primarily from the viscous properties of water.

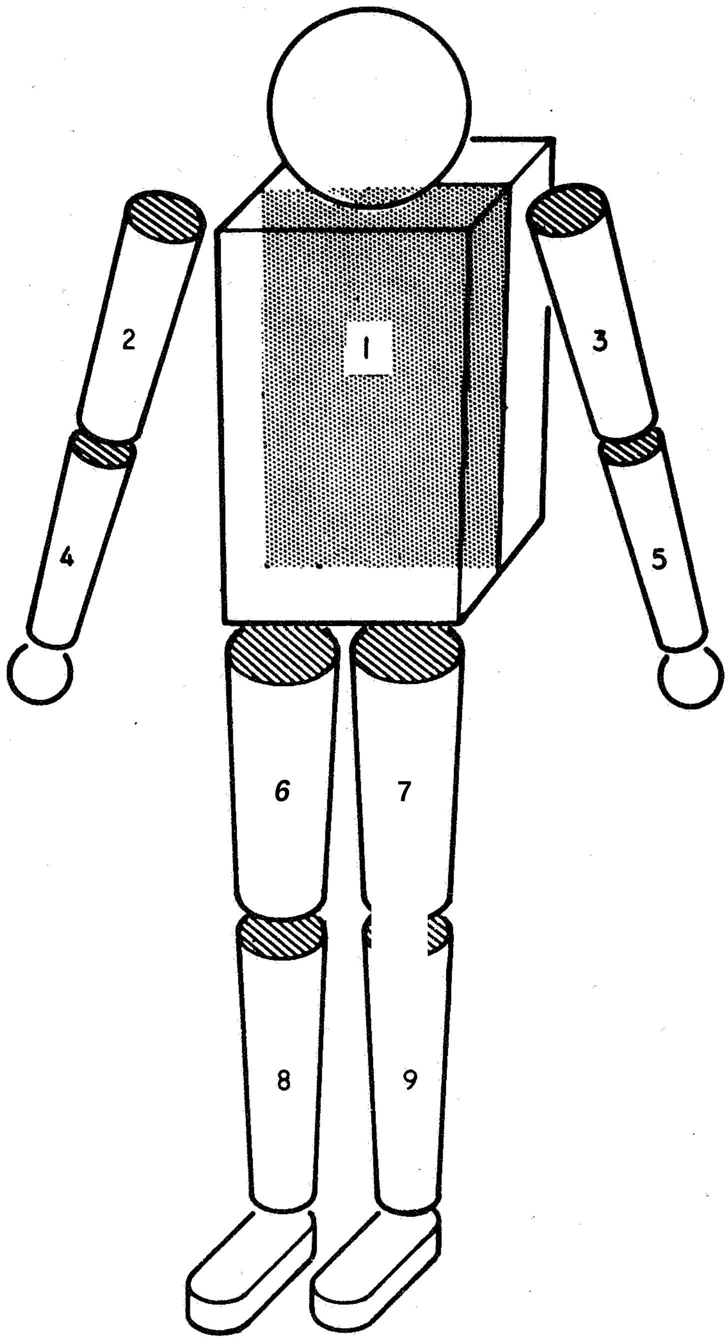


Figure I-9. Matnematical Model

In general, the drag appears partly as normal pressure drag and partly as surface-friction drag. The former results from the distribution of forces normal to the body surface; the latter results from the viscous resistance of water particles against displacement in relation to each other and to the surface of the solid body.

The Reynolds number, known as a parameter, signifies whether the resistance of the motion is dominated by pressure drag or friction drag. Its constituents are the length and velocity V of the moving body, and the density and viscosity of the fluid. Density and viscosity, which are, respectively, the measure of inertia and of frictional resistance to distortion of the fluid, can be assumed to be constant in the water simulation study. The consideration of drag effects then depends mainly on the shape and velocity of the pressure-suited subject.

A pressure-suited subject is definitely not a streamlined object. It may be ideally treated as a composite body of simple geometric shapes, such as cylinders and ellipsoids, usually termed "blunt" objects. Based on average human stature, the assumption may be made that the length of a moving, pressure-suited subject should be 2 to 7 ft depending on attitude. Due to the performance constraints imposed by the pressure suit and regard for the safety of the crew in orbital activities, the subject's velocity range is calculated between 0 and 1.75 fps. At a normal temperature of 65°F, the water has a kinematic viscosity $\nu = \mu/\rho$ of 1.25×10^{-5} sq ft per sec. The Reynolds number range for the water immersion weightless simulation of the maneuvers of the pressure-suited astronaut can therefore be estimated as

$$R = \frac{\rho V \ell}{\mu} = \frac{V\ell}{\nu} \approx 10^3 \sim 10^6$$

when $\ell = 2$ ft, V = 0.01 fps, and $\ell = 7$ ft, V = 1.75 fps, respectively. Such magnitude is commonly termed a "high" Reynolds number.

At high Reynolds numbers, the viscous forces are important only in the very thin boundary layers close to the moving subject. The remainder of the flow behaves as if in an essentially nonviscous fluid. The boundary layer is the region of retarded flow; the motionless layer of water initiates its formation, Around a body of good "Streamlined shape," no separation of the boundary layer occurs. The normal pressure drag is usually very small. This drag results from integrated effect of the normal components of the forces exerted by water over the entire moving body. Most of the drag is due to surface friction resulting from the action of the tangential components of the forces. The surface friction drag may thus be estimated from boundary layer theory. The calculation is greater if the boundary layer is turbulent than if it is laminar. For a blunt body, separation of the boundary layer leads to a large normal-pressure drag, and the surface-friction drag becomes only a small proportion of the total.

Physically, the separation of the boundary layer is caused by the "stall" phenomenon. When a blunt body moves through a stationary fluid, the boundary-layer particles are pushed by the falling pressure downstream from the nose to the shoulder, which is the maximum thickness of the blunt body. A streamlined body with a long tapered tail has a moderate rate of pressure rise from shoulder to tail; in contrast, with blunt objects the rate of pressure rise from shoulder to tail is so high that the boundary-layer particles slow to a halt and may be pushed back by the higher pressure at the tail. A broad eddying wake that consequently forms downstream produces a pressure difference between the forward and rear parts of the body. Such a net pressure drag connected with flow separation is usually many times greater than the viscous drag due tc friction at the surface of the body.

Moreover, the boundary layer with blunt objects is laminar at relatively low speed, which is the case in performing the water-immersion simulation activities. The separation occurs somewhat earlier upstream of the shoulder of the object; the boundary layer is widely separated. The resulting wake has a pressure lower than that associated with the high-speed turbulent case. Hence, the pressure drag becomes relatively higher.

Complex interactions, indeed, occur between the various components of drag; thus, many factors must be considered in determining the damping effects of the water during the performance of various simulated activities. Some factors are, for instance, the surface roughness of the pressure suit and the exposure of the gas-supply breathing system in the water. The foregoing discussion indicates, however, that for low-speed motions in water, the normal-pressure drag causes the damping effect. It is, therefore, important to know the resultant of the pressure forces over the body in the line of undisturbed motion, or the variation in the pressure distribution around the body. The separation of the boundary layer and the wake formation behind the moving body suggest that the dynamic pressure and the projected area normal to the motion are pertinent to the total drag.

The total drag D is customarily expressed as

$$D = C_D \, q \, A \qquad (1-1)$$

where the dynamic pressure $q = 1/2 \, \rho V^2$, and C_D is the drag coefficient, V the velocity of the moving body, ρ the density of water, and A the projected area of the body normal to V. The nondimensional constant C_D is a function of the Reynolds number, determined experimentally. For simple geometrical shapes, C_D vs Reynolds number curves are readily available in numerous textbooks. In regard to drag coefficient for the human body, only limited research has been carried out.

Hoerner (ref. 19) summarized the results obtained by Schmitt's (ref. 20) wind-tunnel investigation. Hoerner showed that the drag coefficient of an average clothed man in a wind-tunnel speed of 100 to 200 fps is between 1.0 and 1.3 for the standing positions, and 5 to 10 percent less without clothing. Most recently, Trout, Loats, and Mattingly (ref. 21) have included in their report a number of drag-vs-velocity curves for the pressure-suited subject performing both the aircraft zero-gravity trajectory and water-immersion simulations. Based on their work, the values of the drag area were calculated by

$$A_D = C_D A = \frac{D}{q} \qquad (1\text{-}2)$$

Table 1-1 lists the results obtained in different tests. The pressure-suited subject simulations in trajectory flight and water immersion seem to supplement Schmitt's wind-tunnel investigation of the clothed subject.

By the principle of dynamic similarity, it is therefore concluded from the two available sources that the drag coefficient C_D for the standing position of the human body immersed in water is between 1.0 and 1.3 when the velocity of motion is below 2 fps. As the comparison showed, the size of the subject, either clothed or pressure-suited, seems to have no effect on the magnitude of the drag coefficient.

Before the accumulated information on drag coefficients can be used in the water-immersion simulation, it is advisable to narrow down the range of 1.0 to 1.3 and to determine specifically its values for various maneuvering positions. For improving the accuracy of scaling and the prediction of actual space conditions, further detailed drag tests in the water are necessary. The average value of drag areas can be calculated by using an average VH/S equal to 0.74 ft^2 of subjects 1 through 8. Table 1-2 includes only the values of those positions which are likely to exist in a programmed task. Until accurate C_D values for complicated maneuvering attitudes are available from elaborate drag tests in water, these data can be adopted for determining the approximate C_D value in preliminary model analysis. The calculation of projected areas, A, for the listed positions becomes possible with the model. The drag coefficient is given by the equation

$$C_D = \frac{A_D}{A} \qquad (1\text{-}3)$$

TABLE I-1

COMPARISON OF DRAG AREA*

$$A_D = C_D A = \frac{D}{q}, \quad FT^2$$

Body Position	Water-Immersion Simulation	Aircraft Trajectory Simulation	Schmitt's Investigation
Standing	8.7	9	9
Crouch	2.4	2.4	2 to 3
Prone	1.2	1.15	1.2

*In arriving at the results, the densities ρ_{water} = 1.94 lb-sec/ft^4 and ρ_{air} = 0.7385 x 0.00176 lb-sec/ft^4 for altitude of 10,000 ft have been assumed.

TABLE I-2

AVERAGE DRAG AREA* OF CLOTHED SUBJECTS I THROUGH 8, A_D, FT^2

Body Position	Yaw Angle, deg	A_D
Standing	0	8.70
Sitting	0	5.74
Supine	180	0.962

*Due to the suit constraints, it is unlikely that any of the two squat positions of Schmitt's investigation can be achieved.

As an entire body, the pressure-suited subject represents a complicated shape. When it maneuvers in water, the complexity of the motions further increases the difficulty of analyzing the damping effects of the water-immersion simulation. The total drag force might be put in terms of the equivalent velocity at the instantaneous mass center of the body. Knowledge of the orientation and rate of the various components of the body is then required. If the damping effects are investigated on a component-by-component basis, however, the problem is more easily solved. Based on the superposition principle, the evaluation of drag force can then directly make use of the orientation and rate of the component.

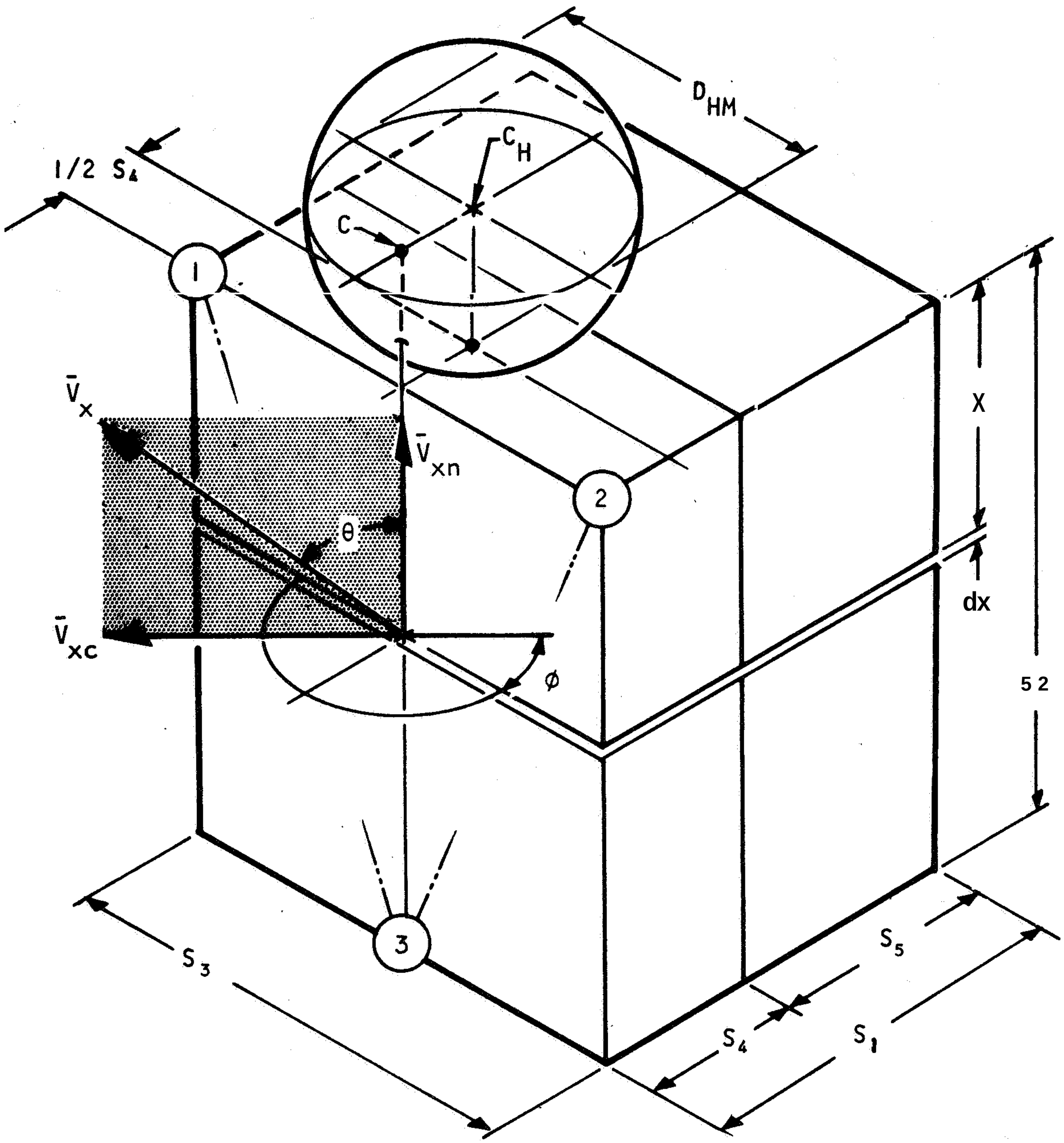
With more accuracy but avoiding unnecessary complexities, a mathematical model of the pressure-suited subject composed of nine segments has been developed.

a. Helmeted head, torso, and backpack tank
b. Righ upper arm
c. Left upper arm
d. Right lower arm and hand (glove)
e. Left lower arm and hand (glove)
f. Right upper leg
g. Left upper leg
h. Right lower leg and foot (boot)
i. Left lower leg and foot (boot)

Figure 3-9 shows the model schematicallv. In arriving at these divisions, the following assumptions are made.

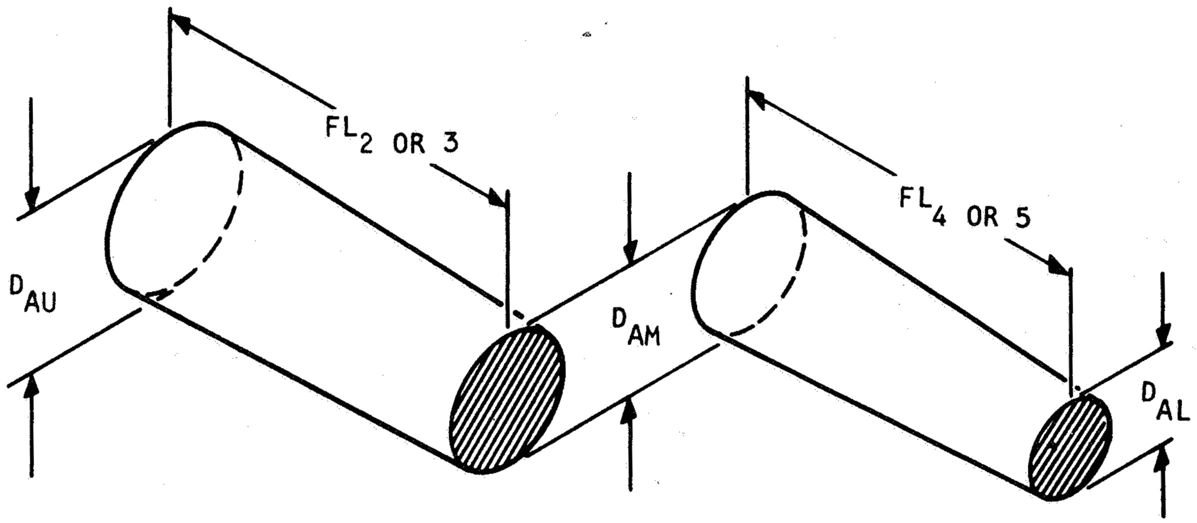
a. The backpack tank is rigidly attached to the subject's torso.
b. Due to the constraints imposed by the suit, the relative movement between head and torso, lower arm and hand, lower leg and foot is negligible or its contribution to the total drag is small.

As shown in Figures 1-10 through 1-12, the segments are assumed rigid, homogeneous bodies of simple geometric shape, hinged at fixed pivot points to resemble the human body. The dimensions of these segments can be calculated when the dimensions of the pressure suit and backpack tank listed in Table 1-3 are given.



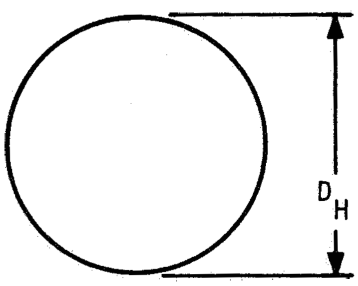
A-22107

Figure 1-10. Torso and Backpack Box, With Positions for Attachment of Accelerometers



(a) UPPER ARM

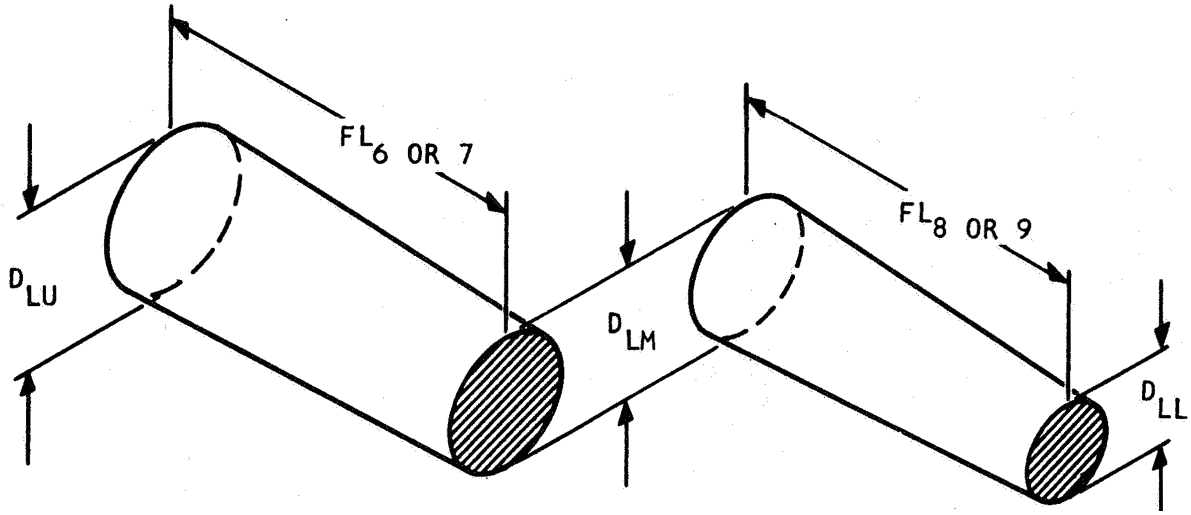
(b) LOWER ARM



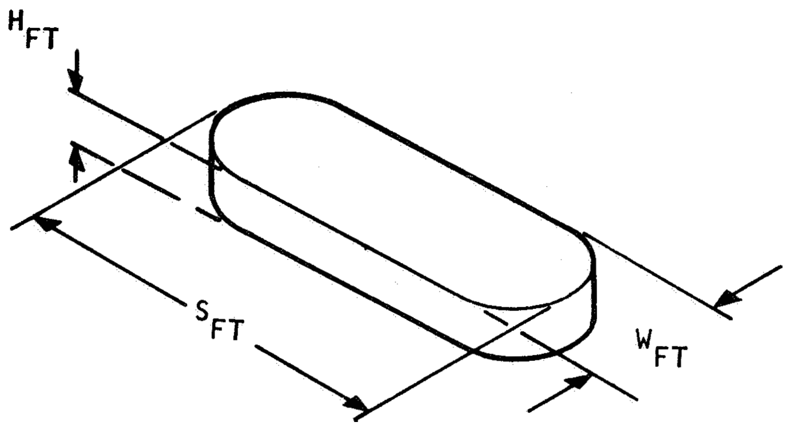
(c) HAND (GLOVE)

A-22106

Figure 1-11. Arm and Hand of Model



(a) UPPER LEG (b) LOWER LEG



(c) FOOT (BOOT)

A-22108

Figure 1-12. Leg and Foot of Mode1

TABLE 1-3

DIMENSIONS OF PRESSURE SUIT AND BACKPACK

Pressure Suit	
	Ankle circumference
CHESB	Chest breadth
CHESD	Chest depth
ELBWC	Elbow circumference
FISTC	Fist circumference (glove)
HFT	Boot height
HLW	Boot heel width
HMC	Helmet circumference
SAL	Lower arm length
SAU	Upper arm length
SFT	Boot length
SLL	Lower leg length
SLU	Upper leg length
STS	Torso height
THIHC	Thigh circumference
TOEW	Boot toe width
UARMC	Axillary arm circumference
WAISD	Waist depth
WRISC	Wrist circumference
XNEEC	Knee circumference
Backpack Tank	
DTK	Tank depth
BTK	Tank breadth
HTK	Tank height

Model geometry is summarized below.

a. Segment No. 1 (Figure (1-10)

(1) Helmet, sphere

$$D_{HM} = \frac{1}{\pi} (HMC) \tag{1-4}$$

(2) Torso and backpack tank

$$S_1 = S_4 + S_5$$

$$= CHESD + DTK \tag{1-5}$$

$$S_2 = \frac{1}{2} (STS + HTK) \tag{1-6}$$

$$S_3 = \frac{1}{2} (CHESB + BTK) \tag{1-7}$$

b. Segments No. 2 and No. 3 (Figure (1- 11)

Upper arm, right circular cone

$$D_{AU} = \frac{1}{\pi} (UARMC) \tag{1-8}$$

$$D_{AM} = \frac{1}{\pi} (ELBWC) \tag{1-9}$$

$$FL_{2,3} = (SAU) \tag{1-10}$$

c. Segments No. 4 and No. 5 (Figure (1-11)

(1) Lower arm, right circular cone

$$D_{AM} = \frac{1}{\pi} (ELBWC) \tag{1-11}$$

$$D_{AL} = \frac{1}{\pi} (WRISC) \tag{1-12}$$

$$FL_{4,5} = (SAL) \tag{1-13}$$

(2) Hand (glove), sphere

$$D_H = \frac{1}{\pi} (FISTC) \tag{1-14}$$

d. Segments No. 6 and No. 7 (Figure 1-12)

Upper leg, right circular cone

$$D_{LU} = \frac{I}{\pi} \text{(THIHC)} \quad 1\text{-}15$$

$$D_{LM} = \frac{I}{\pi} \text{(XNEEC)} \quad 1\text{-}16$$

$$FL_{6,7} = \text{(SLU)} \quad 1\text{-}17$$

e. Segments No. 8 and No. 9 (Figure 1-12)

(I) Lower leg - right circular cone

$$D_{LM} = \frac{I}{\pi} \text{(XNEEC)} \quad 1\text{-}18$$

$$D_{LL} = \frac{I}{\pi} \text{(ANKC)} \quad 1\text{-}19$$

$$FL_{8,9} = \text{(SLL)} \quad 1\text{-}20$$

(2) Foot (boot), rectangular block with rounded ends

$$H_{FT} = \text{(HFT)} \quad 1\text{-}21$$

$$S_{FT} = \text{(SFT)} \quad 1\text{-}22$$

$$W_{FT} = \frac{\left[\text{(TOEW)} + \text{(HLW)}\right]}{2} \quad 1\text{-}23$$

SCALING LAWS

The same tasks performed in space will be carried out underwater; the corresponding metabolic rates will then be calculated with the collected physiological data. Concurrently, the motion histories of tasks will be recorded with accelerometers. For preliminary study, the damping effects of water can be considered as the sole difference between the simulated underwater environment and the weightless space environment. The metabolic rates collected from underwater simulation can be taken as E_{MW}; and E_{MS}, those in space. Furthermore, if E_D is the additional energy consumed during underwater maneuverings due to drag, the scaling law will then be

$$E_{MS} = E_{MW} - E_D \tag{1-24}$$

Thus, the need arises for deriving mathematical equations for the evaluation of drag energy E_D. With the mathematical model to approximate the suited subject, the simplified geometry of the segments, together with the recorded motion history, should provide enough information for the drag force of Equation (1-1) and, consequently, for the drag energy by integrating the force over the distance the segments traversed. Detailed derivation of this E_D equation is discussed below.

Besides metabolic rates, durations of various tasks performed in space must also be predicted. Since it is suggested that the work platform (the external guidance system), which can be calibrated to serve as coordinate frames, be used, accurate time-distance tables for every task can be planned in advance. Through sufficient underwater training, the subject can be expected to complete the tasks in space in due time. That is, time will not be a simulation parameter. Demanding the same performance time in both environments will definitely make it harder for the subject to accomplish the mission underwater. In any event, the additional effort required will be evident in E_D. Clearly, the whole simulation problem depends chiefly on success in deriving a reliable E_D equation.

If the duration of performing a programmed task is t_d and the acceleration $\bar{a}_i(t_j)$ at the joints of segments $i = 1, 2, 3, \ldots, 11$ (Figure 1-13) are given at time $t_1 = 0, t_2, t_3, \ldots, t_j, \ldots, t_m, t_{m+1} = t_d$. With the definition,

$$\Delta t_j = t_{j+1} - t_j \tag{1-25}$$

the result is

$$t_d = \sum_{j=1}^{m} \Delta t_j \qquad (1\text{-}26)$$

The time increments Δt_j can be equal or unequal, as desired.

By direct integration of the acceleration vectors $\bar{a}_i(t_j)$ and by use of the initial position and velocity vectors $\bar{X}_i(o)$ and $\bar{V}_i(o)$, the position and velocity vectors of the joints $i = 1, \ldots, 11$, at time t_j are readily obtainable. They are designated as $\bar{X}_i(t_j)$ and $\bar{V}_i(t_j)$. In a typical segment AB (Figure 1-14), the joint velocity vectors are known at the ends. The velocity vector of a differential segment x distance away from end A is then given by

$$\bar{V}_x = \frac{\ell - x}{\ell} \bar{V}_A + \frac{x}{\ell} \bar{V}_B \qquad (1\text{-}27)$$

The energy expenditure on drag can be evaluated on an interval-by-interval basis. During Δt_j, the drag force acting on the surface of the differential segment is

$$\Delta D = \frac{1}{2} C_D \rho \| \bar{V}_x \|^2 \Delta A_x \qquad (1\text{-}28)$$

where ΔA_x is the projected area of the differential lateral surface normal to $\bar{V}_x$. The segments are assumed to have varying cross-sections. By defining $W(x)$ as the projected width of the perimeter of cross-section $C(x)$ (Figure 1-13) normal to the velocity component $\bar{V}_{xc}$ in the plane of the cross-section, the projected area ΔA_x can then be expressed as

$$\Delta A_x = W(x)\, \Delta x \cdot \mathrm{SIN}\, \theta = \frac{W(x)}{x} \frac{\| \bar{V}_x \times \bar{r}' \|}{\| \bar{V}_x \|} \Delta x \qquad (1\text{-}29)$$

where $\bar{r}' = \frac{x}{\ell}(\bar{r}_B - \bar{r}_A) = \frac{x}{\ell} \bar{r}_{AB}$

For segment AB, the energy expended to overcome the drag during Δt_j can now be evaluated by the equation

$$(\Delta E_D)_j = \sum_{\ell} \frac{1}{2} C_D \rho \| \bar{V}_x \|^2 (\Delta A_x) \cdot (\Delta S_x) \qquad (1\text{-}30)$$

where ΔS_x is the distance traversed by ΔA_x in the direction of $\bar{V}_x$.
By limiting process $\Delta x \rightarrow dx$ and substituting ΔA_x, the energy-expending rate during Δt_j is found to be

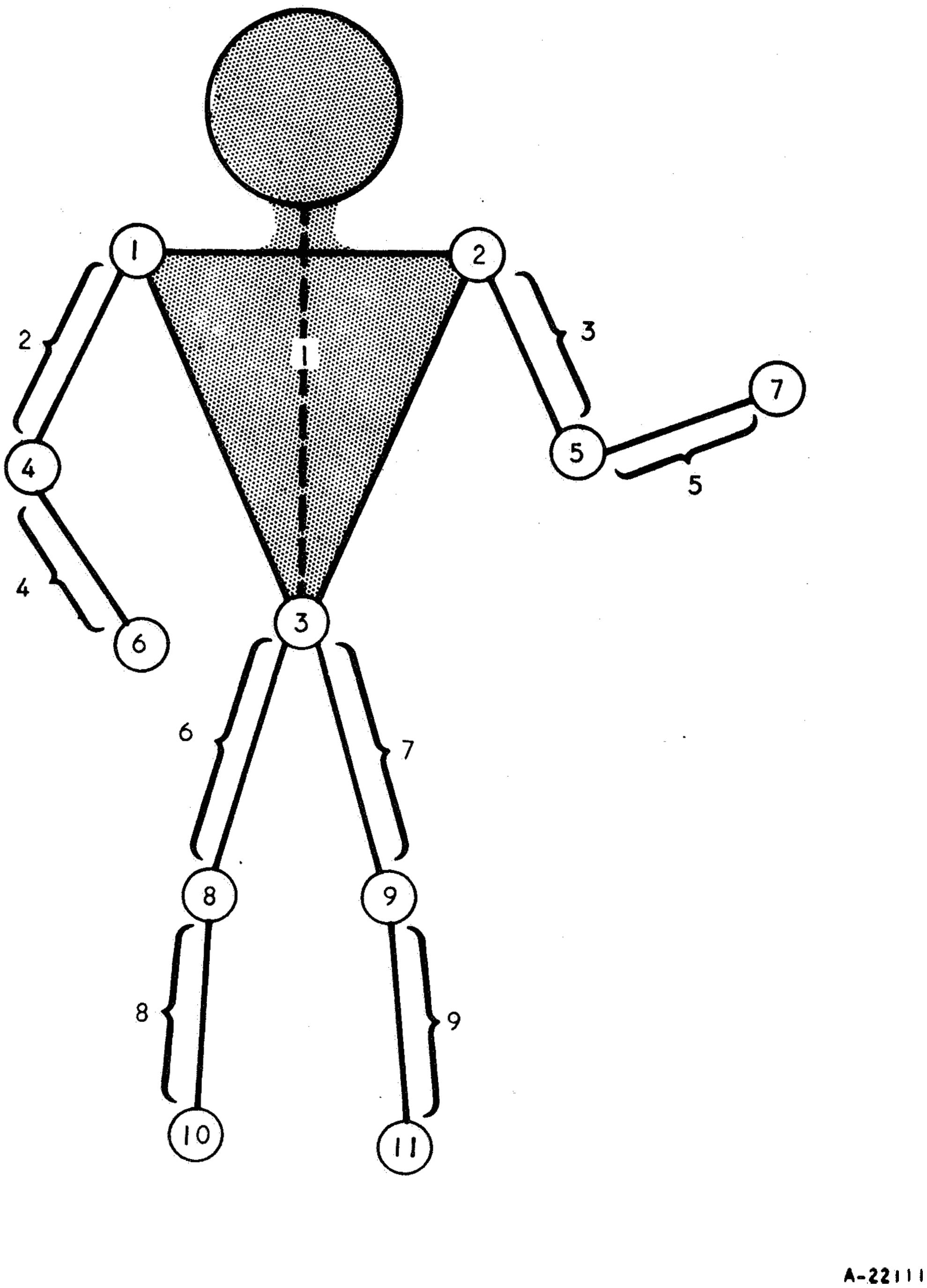


Figure 1-13. Positions for Attachment of Accelerometers in Three Perpendicular Directions

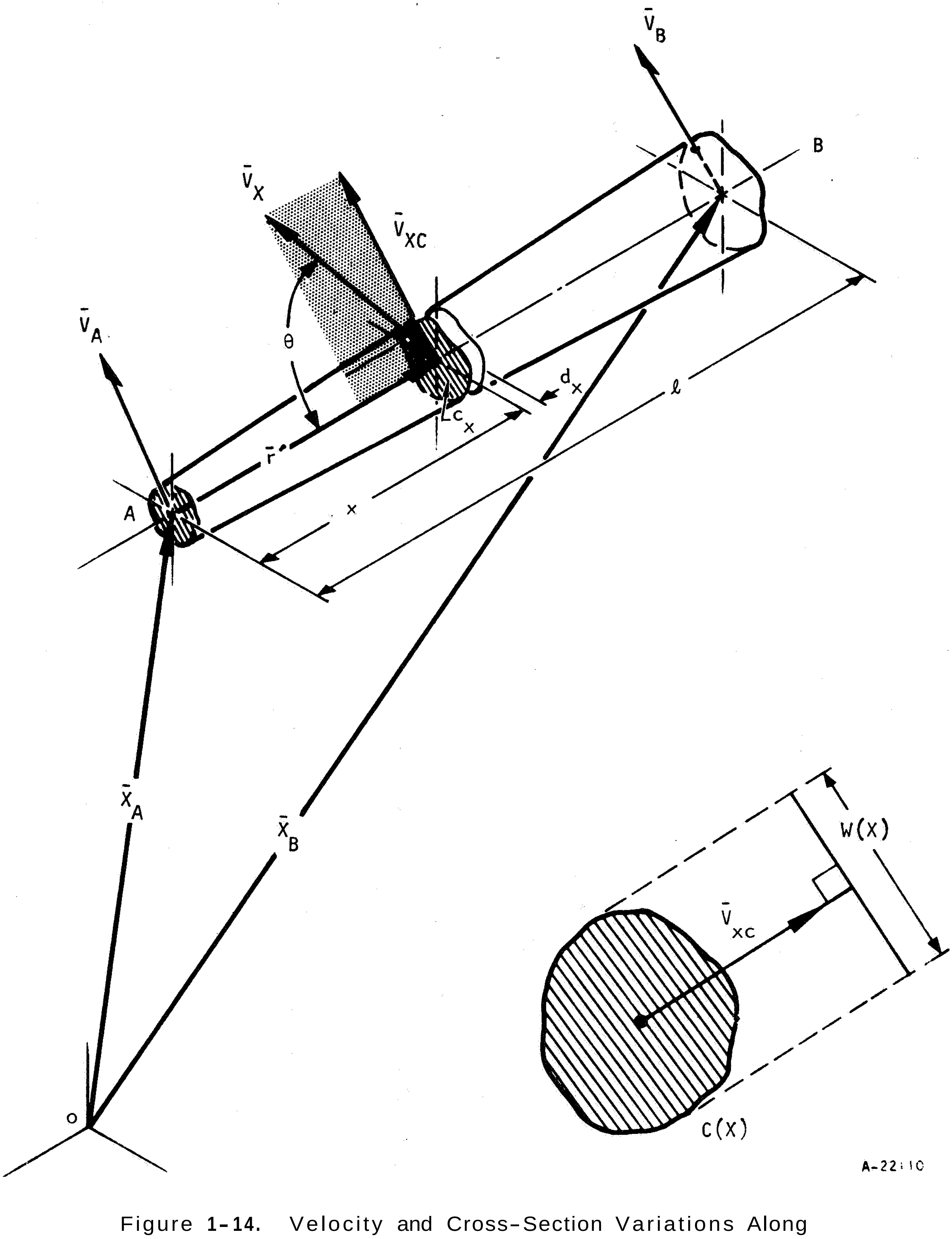


Figure 1-14. Velocity and Cross-Section Variations Along the Axis of Body Segment

$$\left(\frac{\Delta E_D}{\Delta t}\right)_j = \int_o^{\ell} \frac{1}{2} C_D \rho W \frac{|| \bar{V}_x \times \bar{r}' ||}{x} || \bar{V}_x ||^2 dx$$

$$= \frac{\rho}{2\ell} C_D \int_o^{\ell} W(x) || \bar{V}_x ||^2 || \bar{V}_x \times \bar{X}_{AB} || dx \qquad (1\text{-}31)$$

It can be easily shown that in terms of $\bar{V}_A$, $\bar{V}_B$ and $\bar{X}_A$, $\bar{X}_B$, the equation may also be written in the following simple form

$$\left(\frac{\Delta E_D}{\Delta t}\right)_j = \frac{\rho C_D}{2\ell} \int_o^{\ell} W(x) (Ax^2 + B x + C) \sqrt{ax^2 + bx + c}\, dx \qquad (1\text{-}32)$$

where $A = \frac{1}{\ell^2} || \bar{V}_A - \bar{V}_B ||^2$

$B = \frac{2}{\ell} \bar{V}_A (\bar{V}_B - \bar{V}_A)$

$C = || \bar{V}_A ||^2$

and

$a = \frac{1}{\ell^2} || (\bar{V}_A - \bar{V}_B) \quad (\bar{X}_B - \bar{X}_A) ||^2$

$b = \frac{2}{\ell} \left[\bar{V}_A \times (\bar{X}_B - \bar{X}_A)\right] \quad \left[(\bar{V}_B - \bar{V}_A) \times (\bar{X}_B - \bar{X}_A) \right]$

$c = || \bar{V}_A \times (\bar{X}_B - \bar{X}_A) ||^2$

Clearly, the total energy spent on drag of the whole model is the summation of the nine segments by integrating the time variable over the task duration t_d, that is,

$$E_D = \frac{\rho}{2} \sum_{k=1}^{9} \int_o^{t_d} C_D(t) \int_o^{\ell_k} W_k(x) (A_k x^2 + B_k x + C_k)$$

$$\cdot \sqrt{a_k x^2 + b_k x + c_k}\; dx\, dt \qquad (1\text{-}33)$$

where ℓ_k's are the length of segments. As can be seen, subscripts k have been added to W and the coefficients A, B, C and a, b, c since different segments may have different cross-section variations, and the velocity and position histories of their end joints certainly differ. The drag coefficient C_D, a function of the attitude and velocities of component segments, is therefore expressed as a function of time. That W, A, B, C, a, b, and c are, implicitly, functions of time is evident.

The E_D by Equation (1-33) is approximate. The derivations show only the part of energy contributed by drag along the lateral surfaces of segments. The more detailed drag energy results from the component force normal to the shoulder frontal area, and to the gloves, boots, and helmet can be found in Appendix D, Part 1. The calculation are based mainly on Equation (1-30).

E_D of packages that the subject may carry will be added to the total E_D when the configurations of the packages have been defined.

COMPUTER PROGRAMS

Computer programs have been written to facilitate implementation of the scaling study. The program comprises a main program and seven subprograms. Program statement listings, coded in the FORTRAN II language compatible with the IBM 7074 computer available at AiResearch, appear in Appendix D, Part 2. Appendix D, Part 3 presents the flow charts.

MAIN PROGRAM

The main program initializes the data needed in the scaling study by defining physical constants and reading in input suit dimensions and motion histories. Subsequently, it generates the segment models by utilizing Equations 1-4 through 1-23. Finally, by using the subprograms provided, it calculates the drag energy and prints out the scaled result.

INPUT FORMAT

All input data should be punched on IBM 80-column standard cards. The format should be as follows:

Cards 1 to 3 contain the dimensions of the pressure suit and backpack box defined in Table 1-3.

Card 1: Format (10F8.2)

Field 1: ANKC
2: CHESB
3: CHESD
4: ELBWC
5: FISTC
6: HFT

7: HLW

8: HMC

9: SAL

10: SAU

Card 2: Format (10F8.2)

Field 1: SFT ,

2: SLL

3: SLU

4: STS

5: THIHC

6: TOEW

7: UARMC

8: WAISD

9: WRISC

10: XNEEC

Card 3: Format (10F8.2)

Field 1: DTK

2: BTK

3: HTK

Cards 4 to 14 contain initial velocity and position vectors of joints 1 through 11 (Figure 1-13) (Format (10F8.2)).

Field 1: VO_1 x component of initial velocity

2: VO_2 y component

3: VO_3 z component

4: XO_1 x component of initial position

5: XO_2 y component

6: XO_3 z component

Card 15: Format (1615)

Field 1: NDT number of time increment that is m in Equation (1-26)

Time interval cards: Format (10F8.2)

Use as many cards as necessary; each field contains a Δt_j, where $j = 1, 2, \ldots, m$.

Metabolic rate history cards: Format (10F8.2)

Use as many cards as necessary; each field contains a $(\Delta E_{MW})_j$, where $j = 1, 2, \ldots, m$.

Acceleration cards: Format (10F8.2)

Each field contains a A(j,jt,i), where j (time increment index) runs from 1 to m, jt (joint index) fran 1 to 11 and i (component index) from 1 to 3. Using as many cards as necessary, data should be arranged in the following order,

A(1,1,1),A(1,1,2),A(1,1,3),A(1,2,1),

A(1,2,2),A(1,2,3),A(1,3,1),·····,

A(1,11,2),A(1,11,3),A(2,1,1),···

··, A(m,1,1),····,A(m,11,3).

SUBPROGRAM

Subroutine ABC

Calculate A_k, B_k, C_k, a_k, b_k and c_k for $k = 1, \cdots, 9$ defined in Equations (D-5) to (D-10).

Calling sequence:

CALL ABC (AL,AS)

where AL(1,k) = A_k

AL(2,k) = B_k

AL(3,k) = C_k

AS(1,k) = a_k

AS(2,k) = b_k

AS(3,k) = c_k

Subroutine **EQSOL**

Solve systems of linear equations AX = B, where A, X, B are (N, N), (N, 1) and (N, 1) matrices, respectively. It is used to solve w_l in Equation (D-33)

Calling sequence:

CALL EQSOL (A, N, X)

where A is dimensioned A(N, N + 1) with A(i, N + 1) = B(i) for i = 1, 2, . . ., N. Input parameters are A and N; the output parameter is X.

Subroutine SIMPN

Perform the numerical integrations of Equation (1-33) by Simpson's rule.

Calling sequence:

CALL SIMPN (XL, NPT, NTIME, CØEF, AL, AS, SUM)

where XL = ℓ_k segment length

NPT = Number of points adopted for numerical integration

NTIME = An indicator determining whether or not CØEF have to be generated

CØEF = Weighting constants (2 and 4) for the Simpson method, only generated once when NTIME = 2

AL = See Subroutine ABC

AS = See Subroutine ABC

SUM = The calculated result of integration

Subroutine VANDX

Input acceleration vectors, initial velocity and position vectors of the body joints, and the time increments to calculate the velocity and position vectors of the joints at the end of every time increment.

Calling sequence:

CALL VANDX (A, VO, XO, DT, NDT, V, X)

where, all at the body joints,

A = Acceleration vectors

VO = Initial velocity vectors

XO = Initial position vectors

DT = Time increment array

NDT = Number of time increments

V = Velocity vectors at end of every time increment

X = Position vectors at end of every time increment

Function CD (IT)

Determine the value of drag coefficients at the end of time increment Δt_{IT}. Before accurate test data become available, C_D is set equal to 1 for all cases at all times.

Function WABC (X, AL, AS)

Calculate the integrand of the integral in Equation (1-32) when X, AL, and AS are given (See Subroutine ABC for AL and AS).

Function WX (X)

Calculate W (X) of the segments defined in Figure 1-14.

COMPUTER TIME AND OUTPUT FORMAT

The listed programs have been compiled and tested individually. Since no actual data of underwater maneuvering are available at this stage of analysis, the whole program cannot be tested. As a result, no computer time estimate can be made.

For the same reason, the output format is primitive. By using FORMAT (1P4E15.5/), it consists of printing out Δt_j, $(\Delta E_{MW})_j$, $(\Delta E_D)_j$, and $(\Delta E_{MS})_j$ histories. The format will be elaborated as later need arises.

CONCLUSION AND RECOMMENDATION

The model analysis has successfully derived an equation for evaluating the additional energy consumed due to drag, which is assumed to be the main difference between the simulated underwater environment and the weightless space conditions. To predict the metabolic rate of performing tasks in space, a scaling law is thereby established. The method for evaluating the drag energy is by continuous integration over the whole body of the suited subject and also over the surface of the packages the subject may carry. The method will consider the body translations, as well as rotations about the centroid of body segments. Although the approximate mathematical model has been constructed to facilitate development of the scaling law, the integration equation is given in terms of W(X). If desired, the analysis can be extended to make direct use of the external configuration of the pressure suit.

It is felt, however, that for preliminary study of underwater simulation, the present setup suffices to generate accurate results without adding unnecessary complication to the computer program.

Within the scope of motions study, the approach presented represents the best start for the underwater simulation analysis. During analysis of the simulated results, other aspects of scaling not now evident will undoubtedly reveal themselves. The methods for further remedying of the problem will be introduced at that time.

For accurate application of the developed method, reliable input data will be required. The previously suggested combination of accelerometers and film histories of motion will need subsequent digitizing of the motion data to be compatible with the IBM digital computers. Manual conversion would undoubtedly be extremely inefficient and time-consuming. Hence, an automatic device capable of generating the digital input is recommended.

The Data Acquisition System (DAS) seems to be a solution to the problem. AiResearch has successfully employed the DAS in support of the Lunar Excursion Module project and in carrying out the Air Force Engine Analyzer program. These systems are designed to digitize the measurements sensed by the transducers and to record the data on a standard 1-1/2 mil, 1/2-in., polyester-base magnetic tape. This method would use the IBM binary-coded decimal digital format. If the DAS is adopted, a tape containing the motion information of the body joints can be directly read in by the computer to calculate drag energy.

It is indicated in the subprogram FUNCTION CD that $C_D = 1$ has temporarily been set for all attitudes. For producing accurate scaling results, elaborate drag tests have been recommended. Experiments should be conducted to determine the drag coefficients of sane constituent attitudes, moving at various velocities, pertinent to the scheduled movements of underwater tasks. Test results would then enhance interpolation of the other attitudes.

Since the lack of actual data on underwater maneuvering makes it impossible to check out the whole computer program, it is recommended that an input tape be constructed to simulate actual input and serve as a test of the program. This is essential if the program is to be completely checked out and ready to use before data collected in the experimental phase of the study are available and awaiting processing.

DEVELOPMENT OF A PLAN TO VERIFY THE DRAG MODEL AND TO COLLECT CONTINUOUS DRAG ENERGY DATA

The mathematical model of analysis of underwater simulation indicated a need for additional experiments that had previously not been anticipated. It became evident while studying the model and its potential use that experimental tests for determining actual drag coefficients of underwater movements would be a necessary supplement to the previously theoretical drag data. The desirability of a method for collecting drag energy data continuously and on-line in the same manner that the metabolic data in this study were collected also became obvious.

The plans for achieving the mathematical model verification and for performing continuous drag data collection are summarized in the next paragraphs and given in greater detail in AiResearch Report No. LS-66-0879, a formal report submitted during the period of performance of this program.

While simulated tasks are being performed, physiological measurements would be collected for the determination of metabolic rates. In addition, the drag-energy calculations require the recording of a motion history of all the segments of the pressure-suited subject. Movies taken in three perpendicular directions could be used for evaluating the centroid velocities of body segments and to calculate the drag energy on an average basis. Originally, it was believed that by examining a sequence of movie frames based on position changes, the average velocities at centroids could be roughly estimated. Obviously, the final drag results, so derived, will be in error to a high degree. The integration method employed in the model analysis needs only accelerometer or potentiometer readings at body joints. By direct use of these data, methods of finding the velocity, the projected area normal to the velocity, and consequently the drag force have been developed and fully discussed in the analysis contained in LS-66-0879.

Precise drag coefficients are also needed in the drag-energy calculations, in addition to the physiological measurements and motion-history recordings. Shape and velocity of a subject in a fluid determine the value of drag coefficients. Since, during underwater maneuverings, the attitude and velocity of the subject are continually changing, drag-coefficient variations in time should be produced in accordance with the associated history of motions. A survey of literature on drag coefficients indicates that most available data are for simple geometric and streamlined shapes or for large fish, accumulated mainly by NASA and the aircraft industry. Even though the mathematical model of suited subject is approximated by simple geometric shapes, lack of a superposition law demands that experimental tests of composite bodies be carried out because of the unknown interference drags. Although some information on drag on the human body is available, these data are limited ta certain specific attitudes, making necessary more elaborate tests on a variety of attitudes at different velocities in water. These attitudes and velocities should be pertinent to the scheduled movements of the underwater tasks planned. Specifically, it is desirable to construct families of drag-coefficient curves so arranged that by knowing the motion histories of the tasks concerned, determining the drag coefficient becomes a matter of multidimensional interpolation.

To record the motions history of the underwater maneuverings, previously it was thought that the curve readings of the accelerometers attached to the pressure suit, together with movies taken from three perpendicular directions, would provide a continuous supply of data needed for the scaling study. However, acceleration or velocity curves at three perpendicular directions must be generated for each joint of the immersed body. To make the drag-energy calculations by the integration method, these curves have to be manually converted into digital input, suitable for the model analysis computer programs. Because this task would be extremely inefficient and time consuming, an automatic device capable of generating the digital input is required, This requirement is fulfilled by a data acquisition system (DAS) which has been successfully used by AiResearch in support of the lunar excursion module project and in carrying out the Air Force engine analyzer program.

This system is designed to digitalize the measurements sensed by the transducers and to record the data on a standard 1-1/2-mil-thick, 1/2-in.-wide polyester-base magnetic tape by using the IBM binary-coded decimal (BCD) digital format. The BCD format is one of the most standard computer languages currently being used in the industry. A data acquisition system provides the necessary information compatible with the existing tape readers and digital computers. Use of the existing DAS for data collection of underwater maneuverings will result in increased data reliability and reduced operational costs.

SECTION 2

FACILITIES AND APPARATUS

INTRODUCTION

The general facilities used for these tests are part of the Los Angeles Facility of AiResearch Manufacturing Company, a division of The Garrett Corporation. Figure 2-1 shows the general layout of the facility.

UNDERWATER TESTING FACILITY

General

The underwater testing facility was constructed to simulate weightlessness in a pressurized suit using neutral buoyancy techniques.

Figure 2-2 gives a general view of the tank illustrating the various features of the facility required to support the experimental activities. The tank is 30 ft in diameter and 21 ft in height, and provides a 20-ft depth of water. The stairway and catwalk around the top are *4* ft wide and of steel construction with a concrete fill of *4* in. The jib and electrically operated jib hoist are used to install and remove equipment. The corrugated structure attached to the side of the tank is used as the instrumentation recording and control room. An 18 in. square porthole in the tank is within the control room for observations and photography. There are two additional portholes at a *5* ft, *4* in. level, one opposite the control room and one perpendicular to this on the far side of the tank. Lighting provisions consist of three clusters of five flood lights symmetrically spaced about the upper elevation of the tank and four 500-watt underwater pool flood lights symmetrically located between the portholes 6 ft above ground level.

Figure 2-3 shows the pumping, filtering, and heating equipment necessary for water conditioning. The main electrical junction box is shown in the background.

Figure 2-4 is a photograph taken from the porthole in the control room showing the interior of the tank. The platform shown is the fixed platform used for all operations. There is a movable, lowering and raising platform (not shown) adjacent to this porthole of the same dimensions as the fixed platform. There are three symmetrically spaced ladders, one of which is shown in Figure *2-4.*

Figure 2-5 shows the "hookah" pumping station which is located under the stairway and which provides an air source for scuba divers. Scuba tanks are used mainly for standby or emergencies,

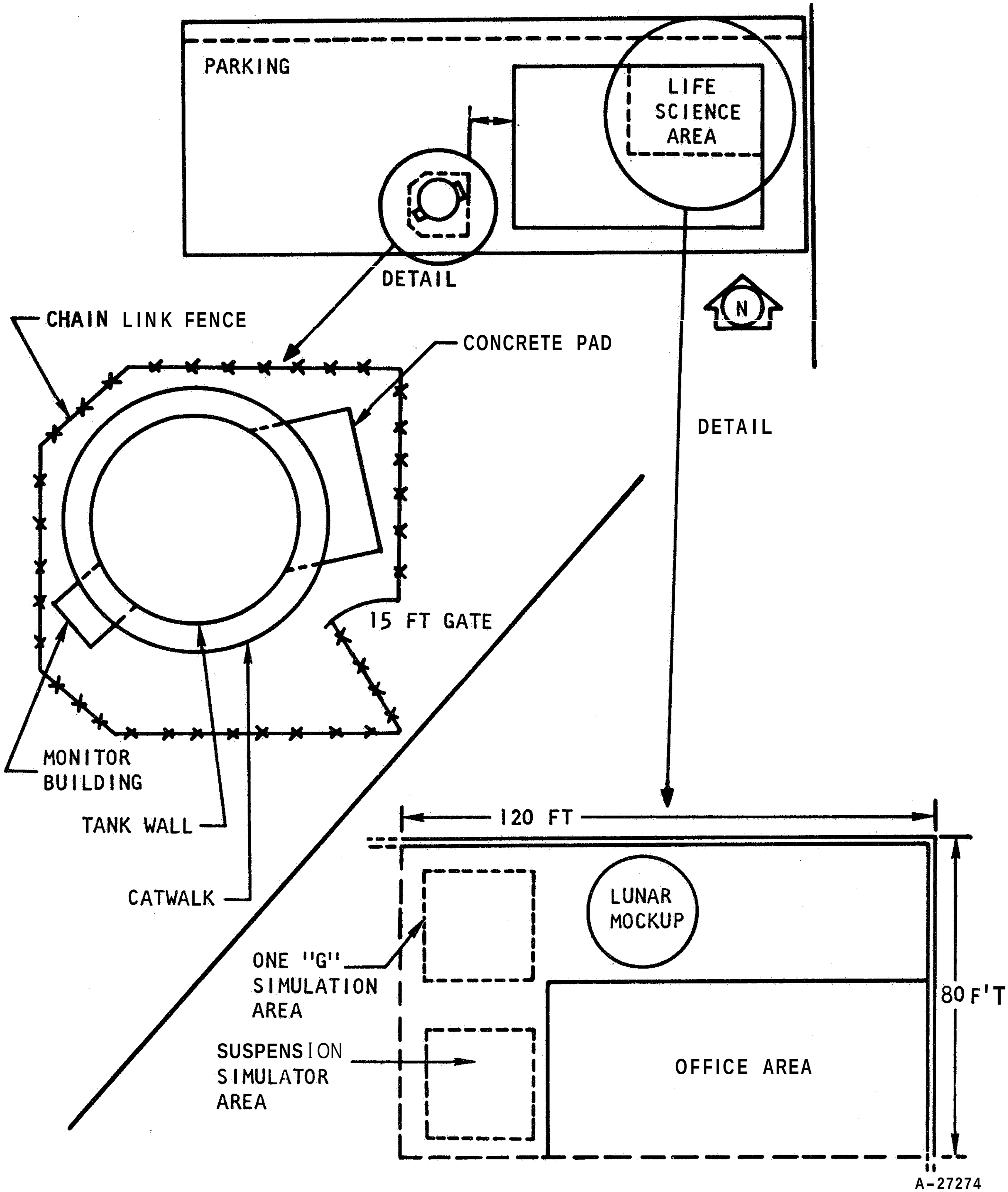


Figure 2-1. AiResearch Douglas Street Facility

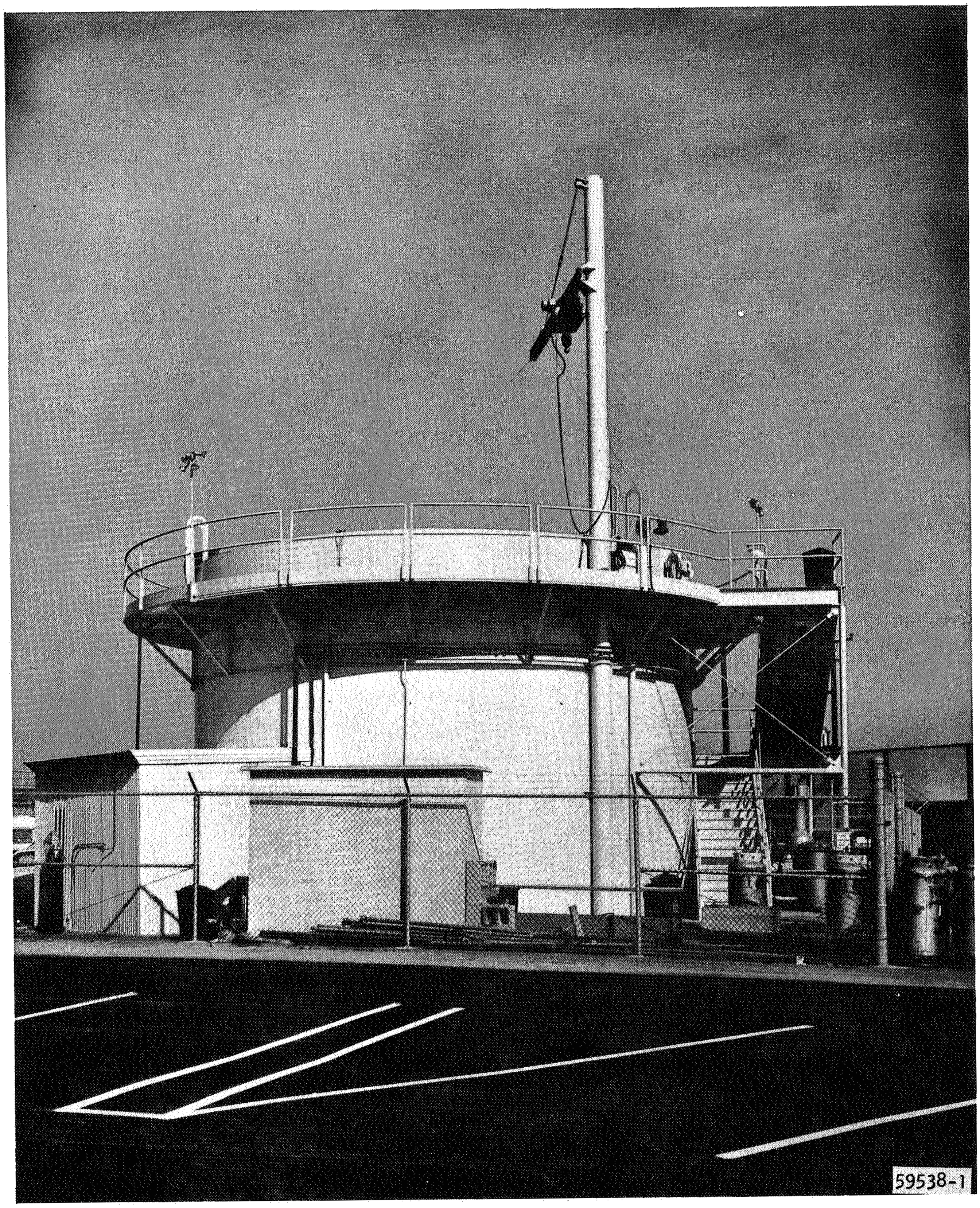


Figure 2-2. Underwater Testing Facility

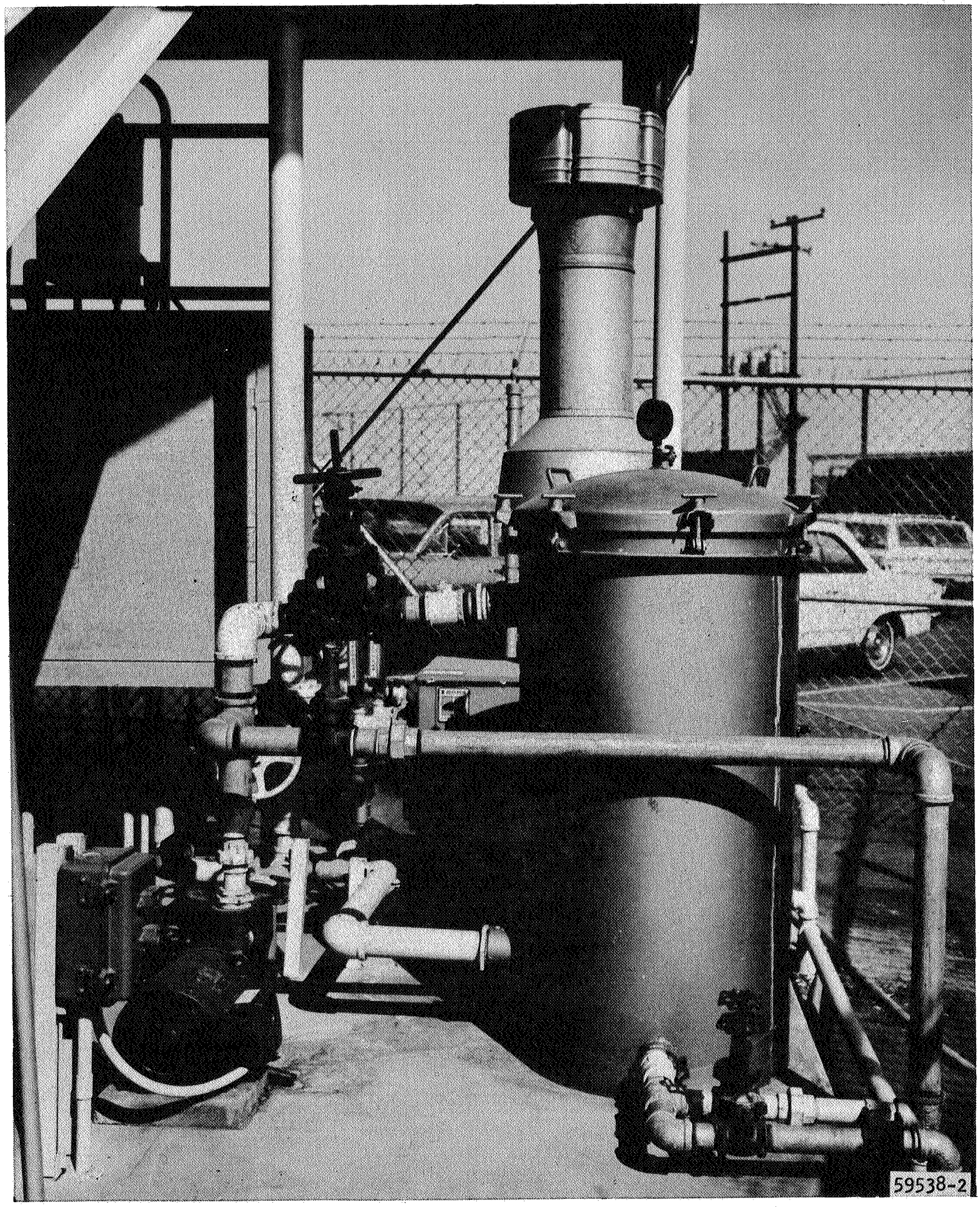


Figure 2-3. Water Conditioning Equipment

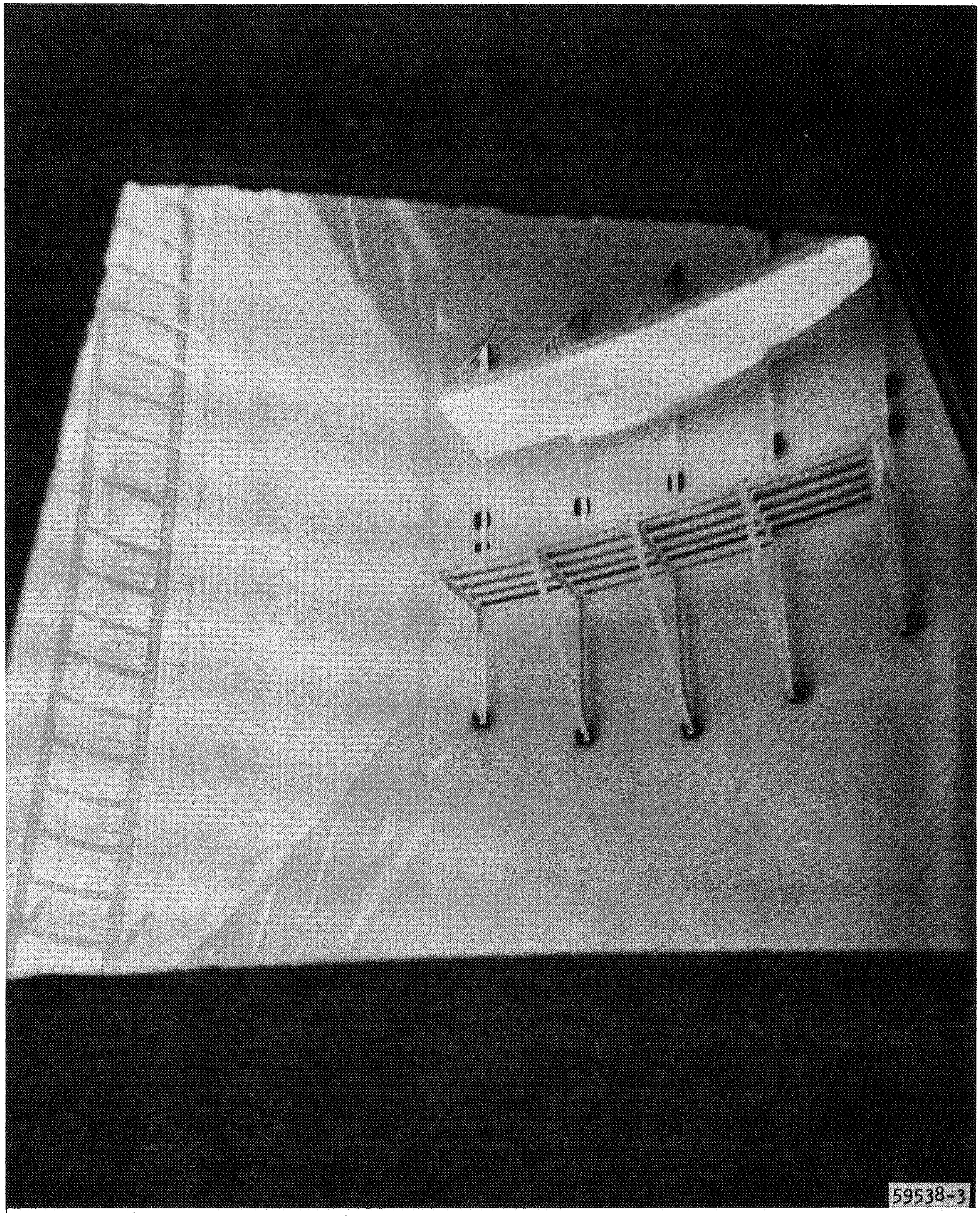


Figure 2-4. Water Tank Interior

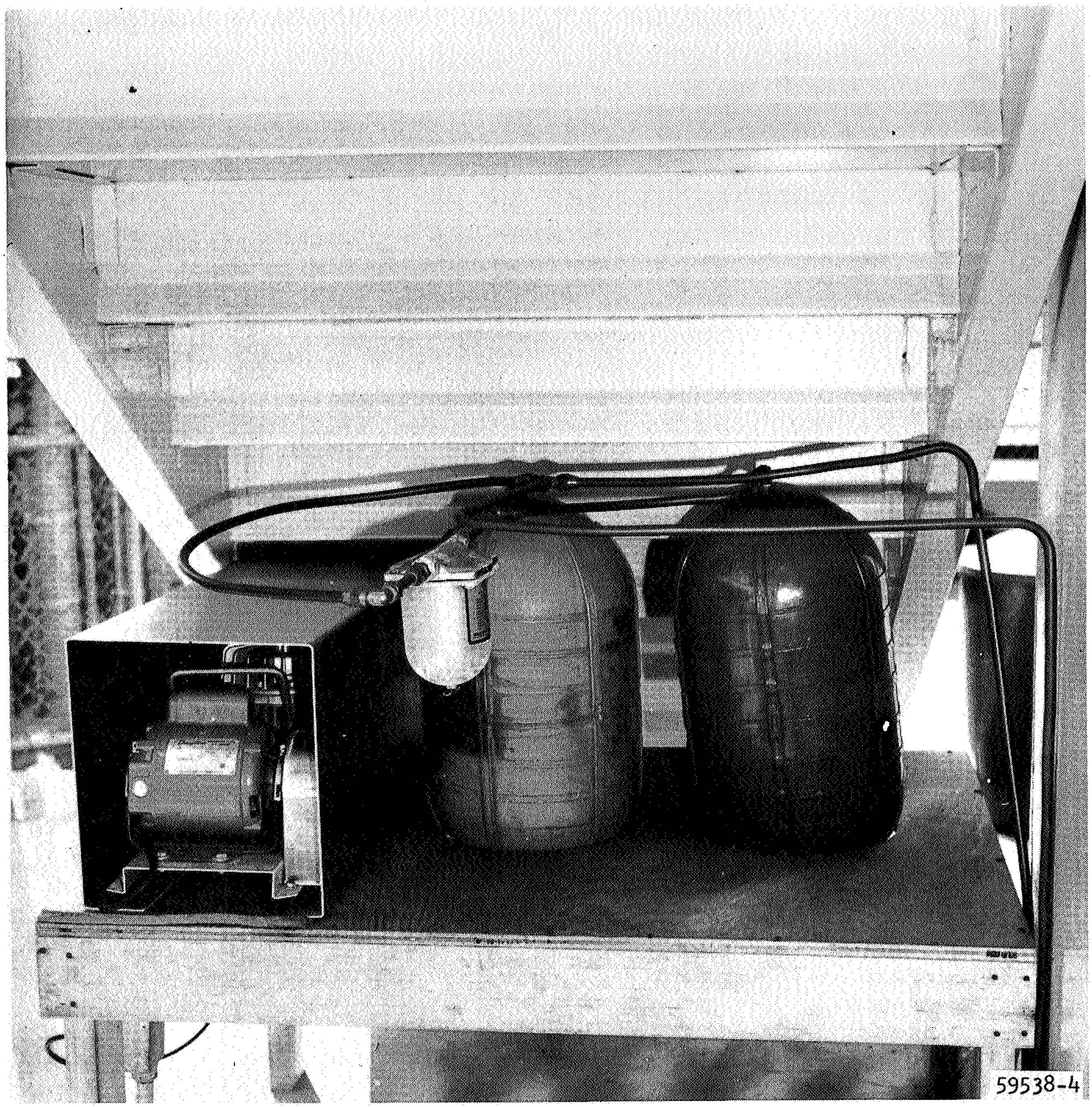


Figure 2-5. "Hookah" Pumping Station

Figure 2-6 provides a view of the tank from a position at the top next to the jib boom. Two ladders, two underwater lights, one porthole, the fixed platform, and one upper-elevation light cluster are shown.

Underwater tests were set up so that the main part of the test sequence would take place in the principal test area shown in Figure 2-7.

Maintenance

The water pH and chlorine content of the water were checked four times each week and adjusted as necessary. The pool was vacuumed once each week. The water was filtered through the pumping and filtering system; the filter was a typical heavy-duty filter using canvas bags and diatomaceous earth. The pump capacity was 250 gal per min; a complete tank volume was, therefore, conditioned approximately every 7 to 8 hr. The water temperature was maintained by adjusting the heater temperature control, the flow through the heater, and the cycling of the pumping system.

SIX-DEGREES-OF-FREEDOM SIMULATOR

A six-degrees-of-freedom simulator (Figures 2-8 and 2-9) is utilized to simulate weightlessngss. The six degrees are provided as follows: (1) the gimballed attach point provides roll freedom, (2) the cable-to-frame attachment point provides pitch freedom, (3) the swivel joint in the cable suspension provides yaw freedom, (4) vertical freedom is accomplished by a counterbalance on the suspension cable through pulling on the overhead, (5 and 6) the two lateral degrees of freedom are obtained through the overhead support mounted on high-quality roder trucks.

The frame is a light-weight tubular aluminum structure with adjusting provisions at the center for vertical and lateral movement, and on the cable attach point for fore and aft movement. These adjustments provide the variability necessary to balance the suited subject with a minimum amount of ballast.

The pressure suited subject is mounted in a formed fiberglass shell attached to the center pivotal point. The Y-shaped webbing harness and a circumferential belt retain the subject in the simulator.

ONE-G TEST CONFIGURATION

Tests were conducted in the one-g environment in shirtsleeves and in a pressurized space suit. Figures 2-10 and 2-11 show the suited condition. The one-g suited and unsuited conditions required a platform to raise the subject to a nominal working height.

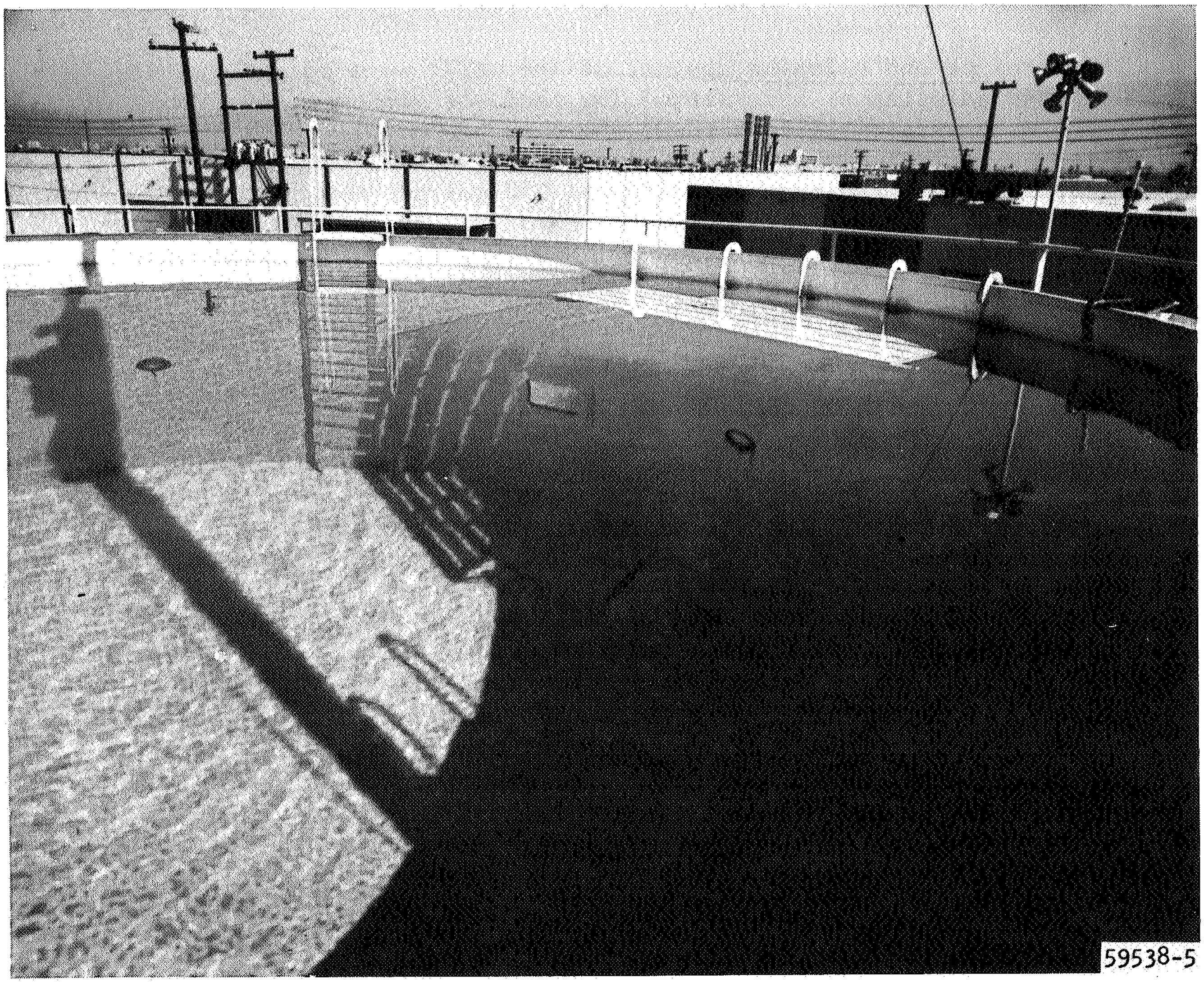


Figure 2-6. Top View of Water Tank

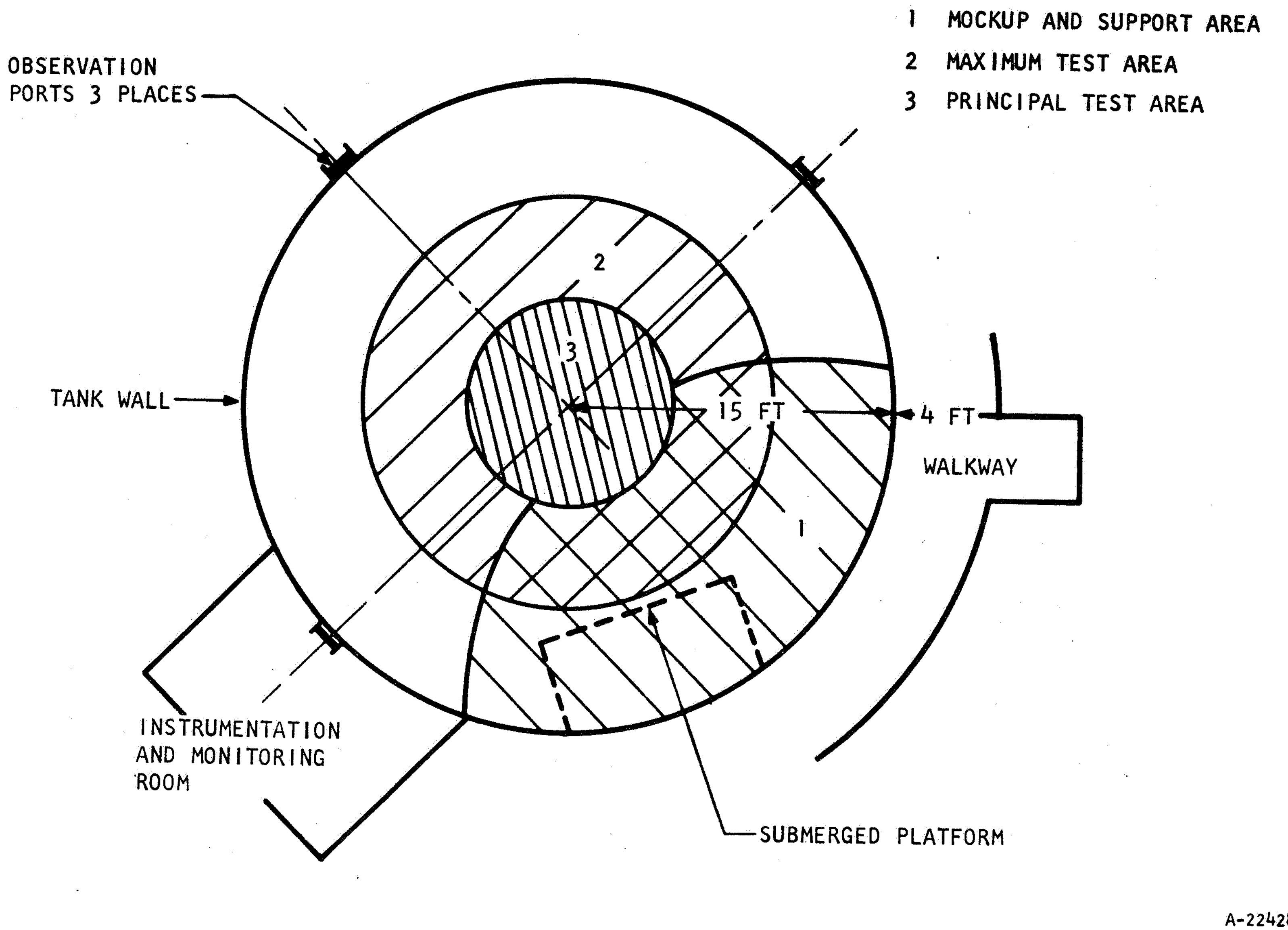


Figure 2-7. Schematic of Tank Work Area

Figure 2-8. Final Balancing in Six-Degrees-of-Freedom Simulator

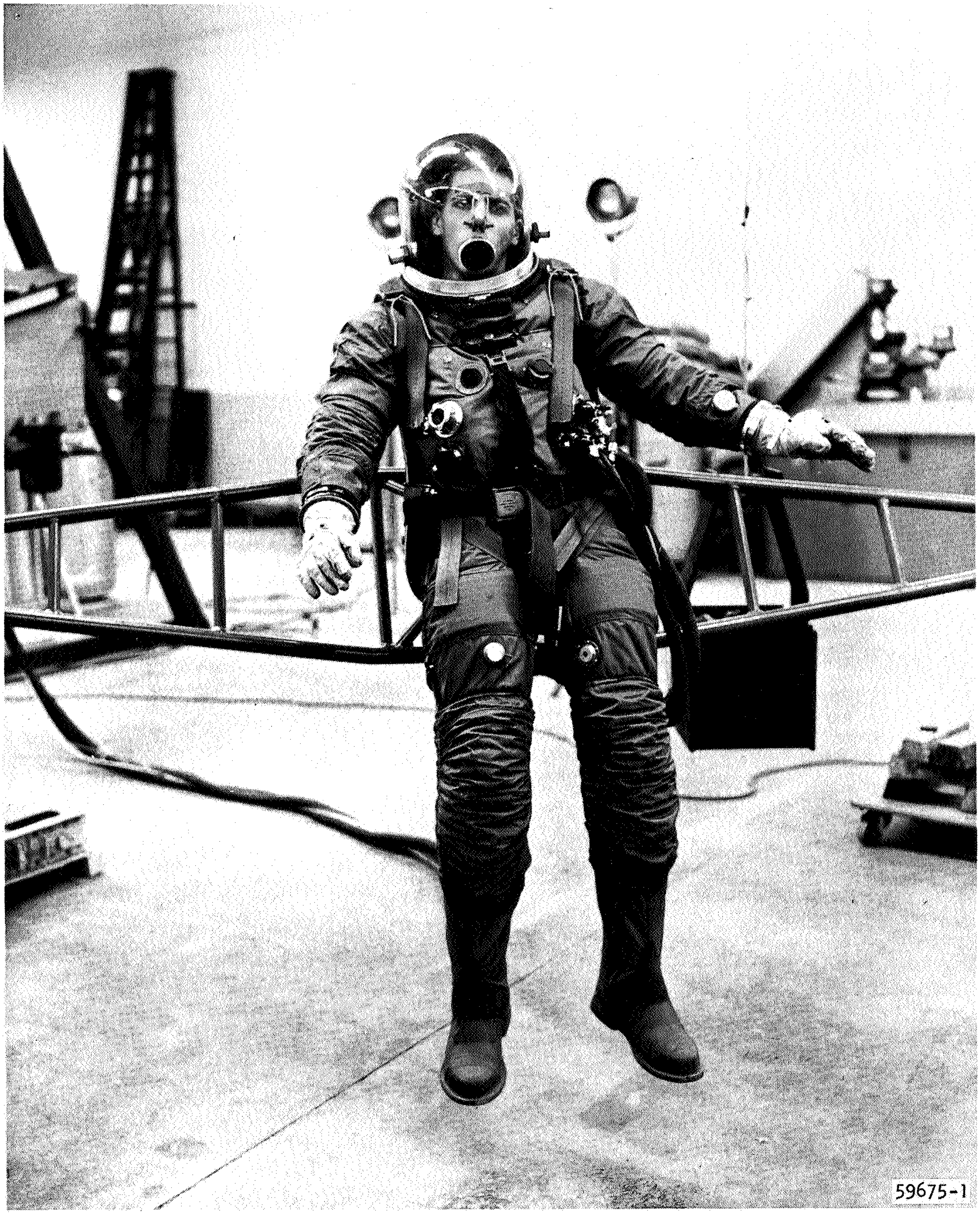


Figure *2-9.* **Subject Forcing Motion in Six-Degrees-of-Freedom Simulator by Body Positioning**

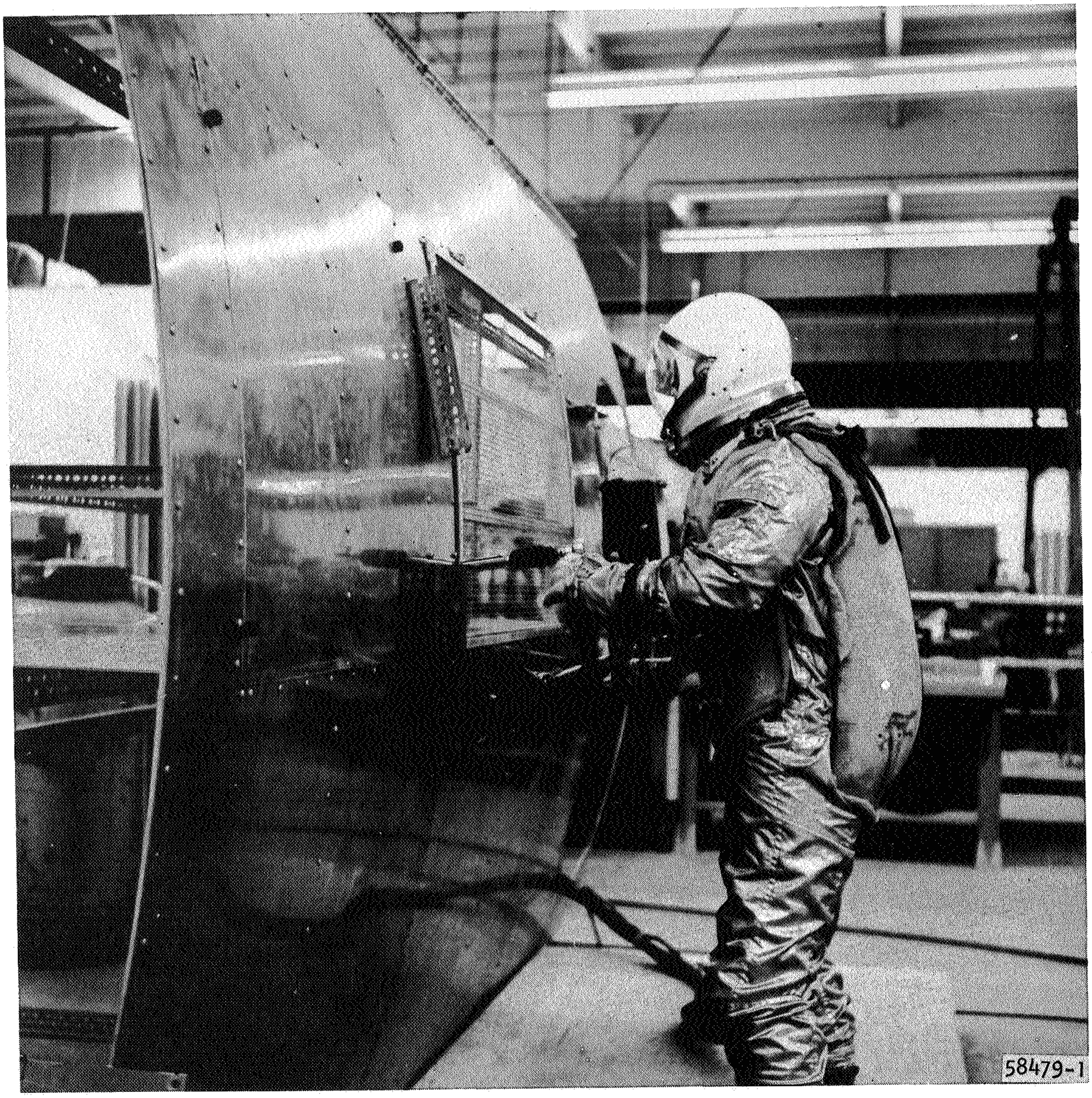


Figure 2-10. One-G Suited Maintenance Test (Hatch Removal)

Figure 2-11. One-G Suited Maintenance Test

MOUNTING SHELL FOR NEUTRAL BUOYANCY

A fiberglass shell was made to fit the torso of the pressure suit. This shell provided the mounting structure for the lead weights required to establish neutral buoyancy and for attachment of miscellaneous equipment and restraint devices. Figure 2-12 illustrates the use of the shell in the one-g tests. Figure 2-13 shows the front part of the shell with the lead weights attached. The cuff weights shown in Figure 2-13 were found to interfere with work. By the proper addition of weights on the shell and in the back pack, very good neutral buoyancy could be obtained for all body positions. Figure 2-14 shows the back shell with a ballast pack attached. The ballast pack has the same basic dimensions as the Portable Environmental Control System (PECS). The weights inside this pack were brass weights threaded so that the position of the weights could be changed by screwing them up or down. The ballast pack is dimensionally similar to a present space back pack system. A cooling pack which is also shown was used for suit cooling and for initial underwater test pressurization and ventilation.

INSTRUMENTATION AND SUIT ECS

The instrumentation and suit environmental conditioning system was similar in each test with a pressure-suited subject. Figure 2-15 is a schematic of the complete system. Inlet and outlet gas composition was determined by sample analysis with a mass spectrometer. Oxygen and carbon dioxide volume percents were determined and were recorded on a Leeds Northrup strip chart recorder which is part of the mass spectrometer. Electrocardiograms and oral temperatures were recorded on a Sanborn two-channel strip chart recorder. Oral temperature was measured with a thermistor placed in the helmet in such a position that the subject could place it in his mouth with his tongue. This thermistor was measured with a copper-constantan thermocouple placed in the ventilation outlet fitting at the suit. This was recorded on a 24-channel Brown recorder. Communication with the subject was maintained by means of an aircraft-type, low-impedance intercommunications system. This required the replacement of the helmet microphones supplied with a Gemini suit. Additional instrumentation consisted of motion and still photography and a special sequence timing board. The special timing board is shown in Figure 2-16. Three stopwatches are actuated by a bar mechanism operated by the observer at specific predetermined events. This actuation stops one watch, which had to be started at the beginning of the event, and starts the following stopwatch for the beginning of the next event. The third stopwatch is reset to zero at the same time so that it is ready to start at the initiation of the following event. A fourth stopwatch is used to determine the total elapsed time of a sequence of events.

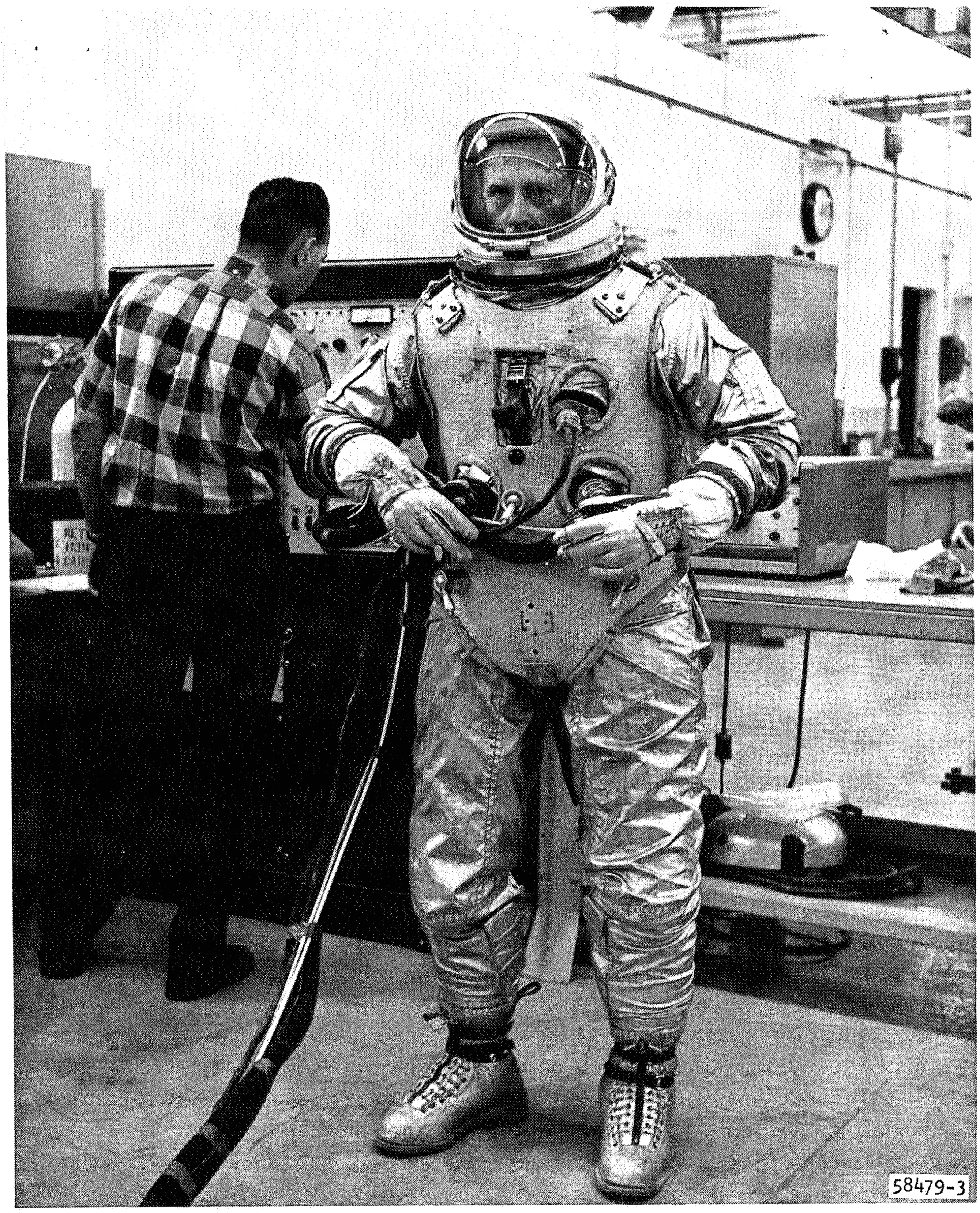


Figure 2-12. Suited Test Subject With Shell

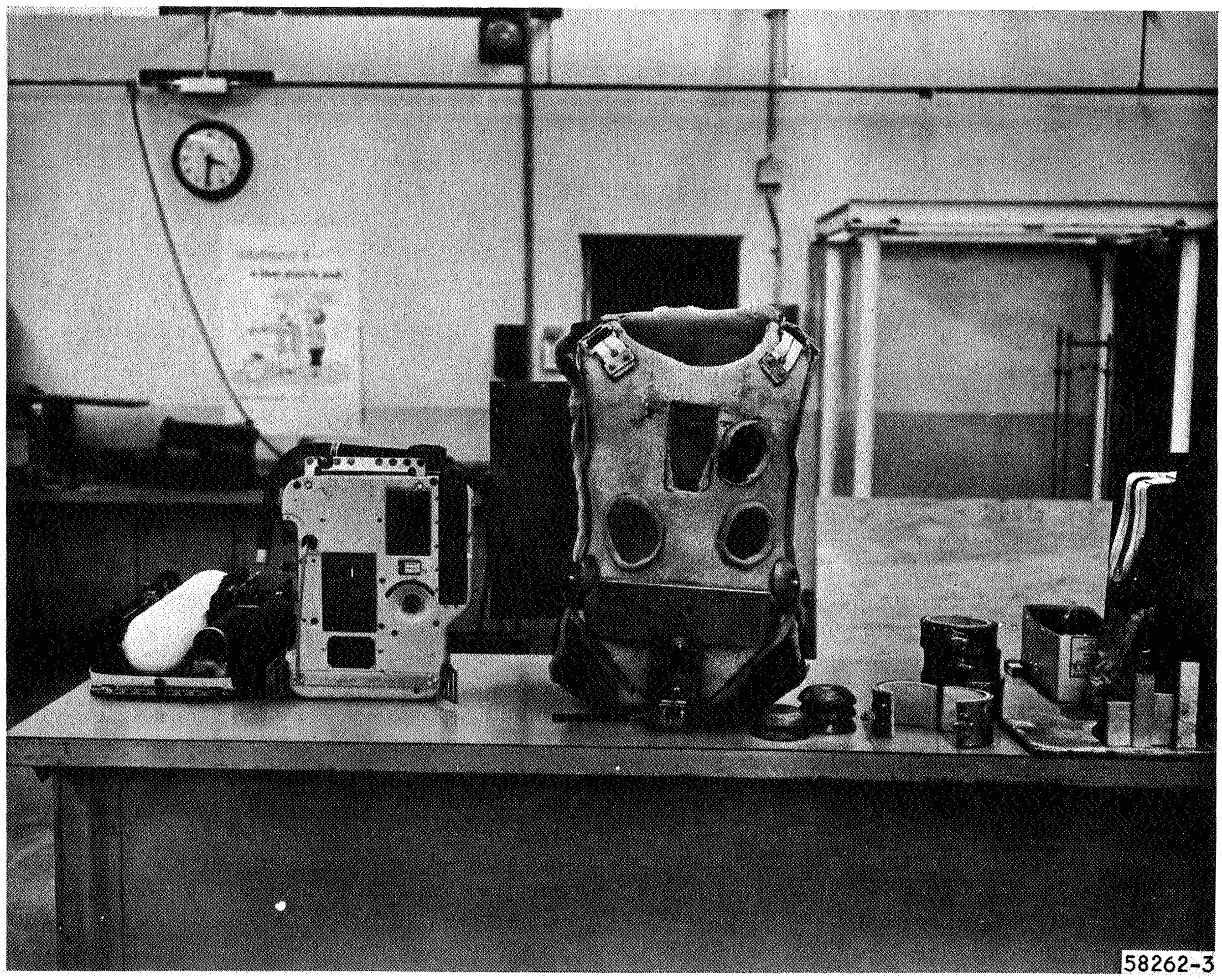


Figure 2-13. Fiberglass Shell to Which the Lead Weights and Restraints Were Attached

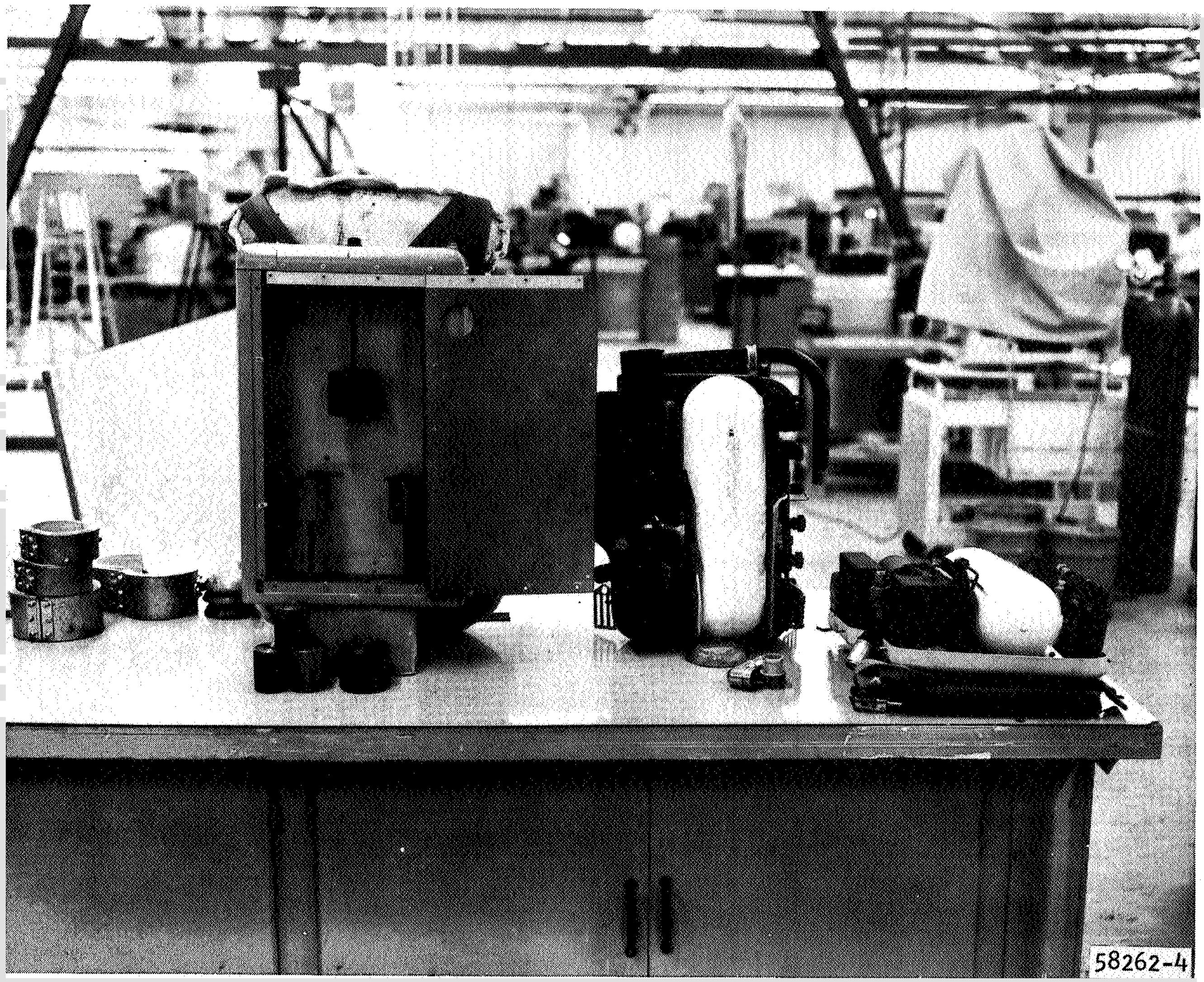


Figure 2-14. Fiberglass Shell With Ballast Pack

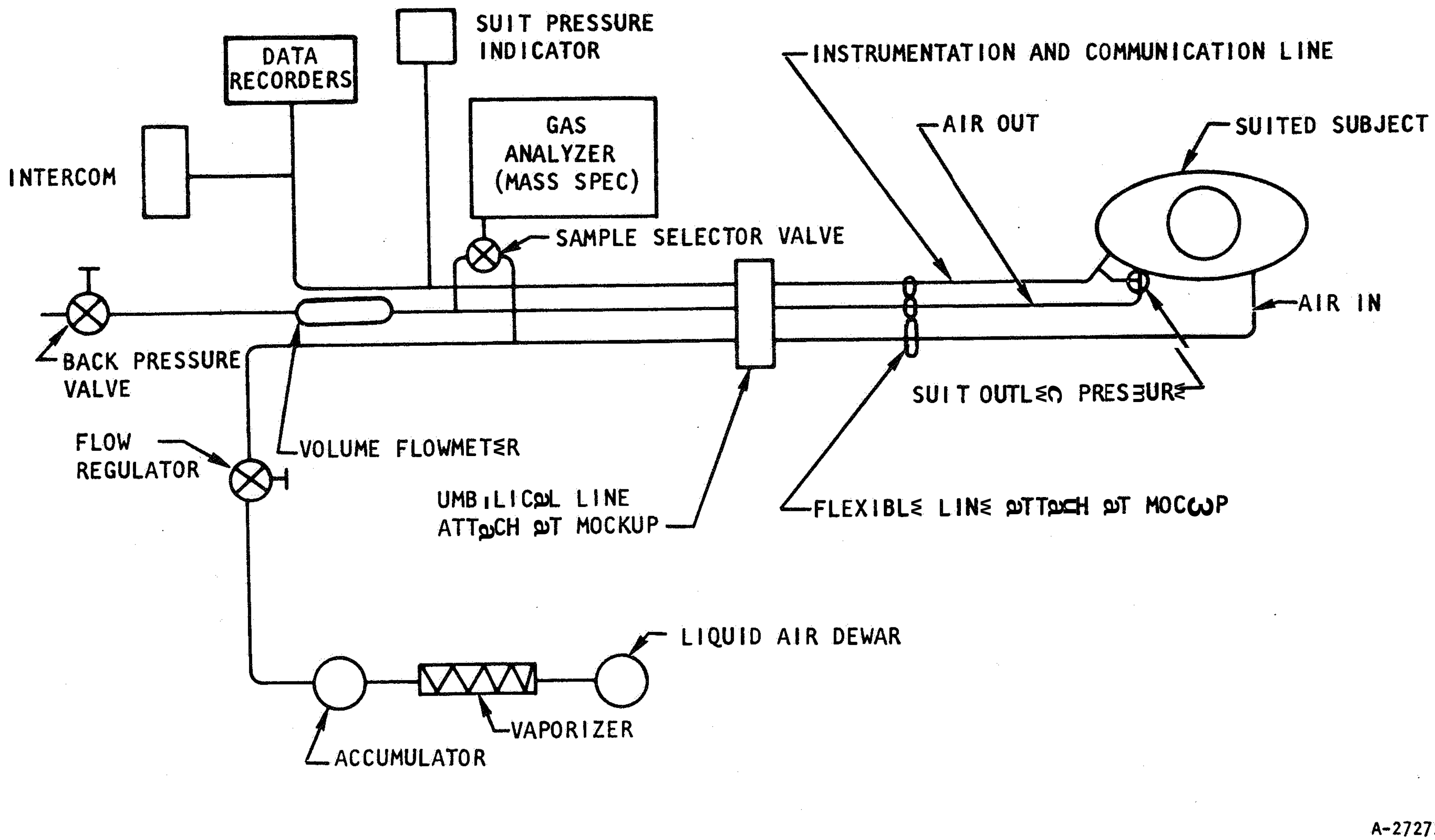


Figure 2-15. Instrumentation and Suit ECS Schematic

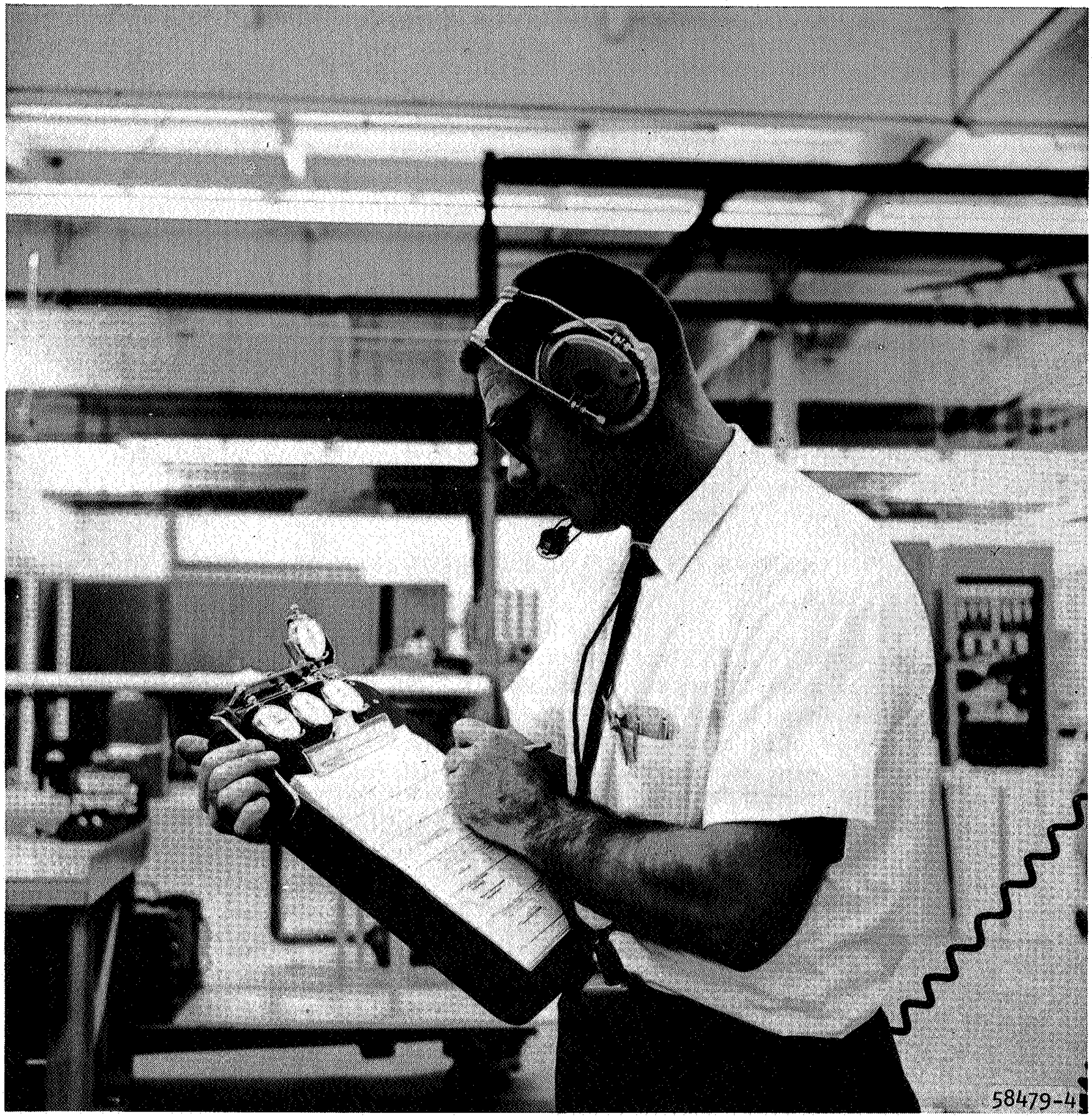


Figure **2-16.** Sequence Timing Board

The ventilating gas for environmental control was supplied from a Dewar of liquid air through an ambient vaporizor (heat exchanger), then to an accumulator. The accumulator was found necessary for mixing the vaporized gas because of the forge fluctuation in oxygen and nitrogen vapor pressures. The vaporized air was introduced to the suit circuit through a flow control regulator. Suit pressure was maintained by adjusting the backpressure valve. The flow was maintained between 3.7 and 5.3 cfm by adjustment of the flow control and backpressure valves, and was measured with a mass flowmeter. Flexible hoses approximately 20 ft long were used for the one-g and six-degrees-of-freedom tests. In the underwater tests, the ventilating gas was introduced into 1-1/2-in.-dia copper tubing which ran from the control room to the top of the tank, down to the bottom of the tank, and to the mock-up area. Flexible hoses, 30 ft long and with a 1-in. diameter, were attached to the copper tubing and then to the pressure suit. The copper tubes were approximately 70 ft long. Suit pressure was measured with a differential pressure transducer at the suit outlet fitting and was displayed on an indicator for monitoring purposes.

MOCKUPS FOR NEUTRAL BUOYANCY TESTS

The mockups used in this test program are illustrated in Figures 2-17, 2-18, and 2-19. The basic structure shown as the spacecraft mockup was used as the basic structure for all mockups. The structure consisted of "dexeon" angle pieces with curved stringers attached for the skin. The stringers were of 1/4-in. plate, 21 in. wide, and rolled to a 10-ft radius. An aluminum skin 1/8 in. thick was attached to the stringers to simulate the cylindrical surface of a space vehicle 20 ft in diameter. Two access panels were provided, one 30 by 46 in. and the other 30 by 30 in. The access panels were attached at four points; at each point, provisions for more than one size fastener were made for the variations in fasteners to be used. The large access opening was used for all maintenance tasks and the provisions for the various tasks; i.e., fastener size location and all other variations were built into the work area.

The antenna mockup used the maintenance mockup as a base for supporting the antenna. The antenna consisted of a welded single piece, tubular boom structure attached to the maintenance mockup at three points. The dish structure was constructed of thin-wall aluminum tubing secured at the joints with aluminum disks drilled for the same outside diameter of the tubes. These holes were drilled at an angle to provide the simulation of curve antenna dish with a radius of 10 ft. The tubes were secured in the hole with wing-type set screws.

The packaged folding panel test involved the application of to the antenna dish structure of triangular pieces made from aluminum strips and hardware cloth. These were joined together in sets of four panels each at the apexes with short pieces of bungee cord. These

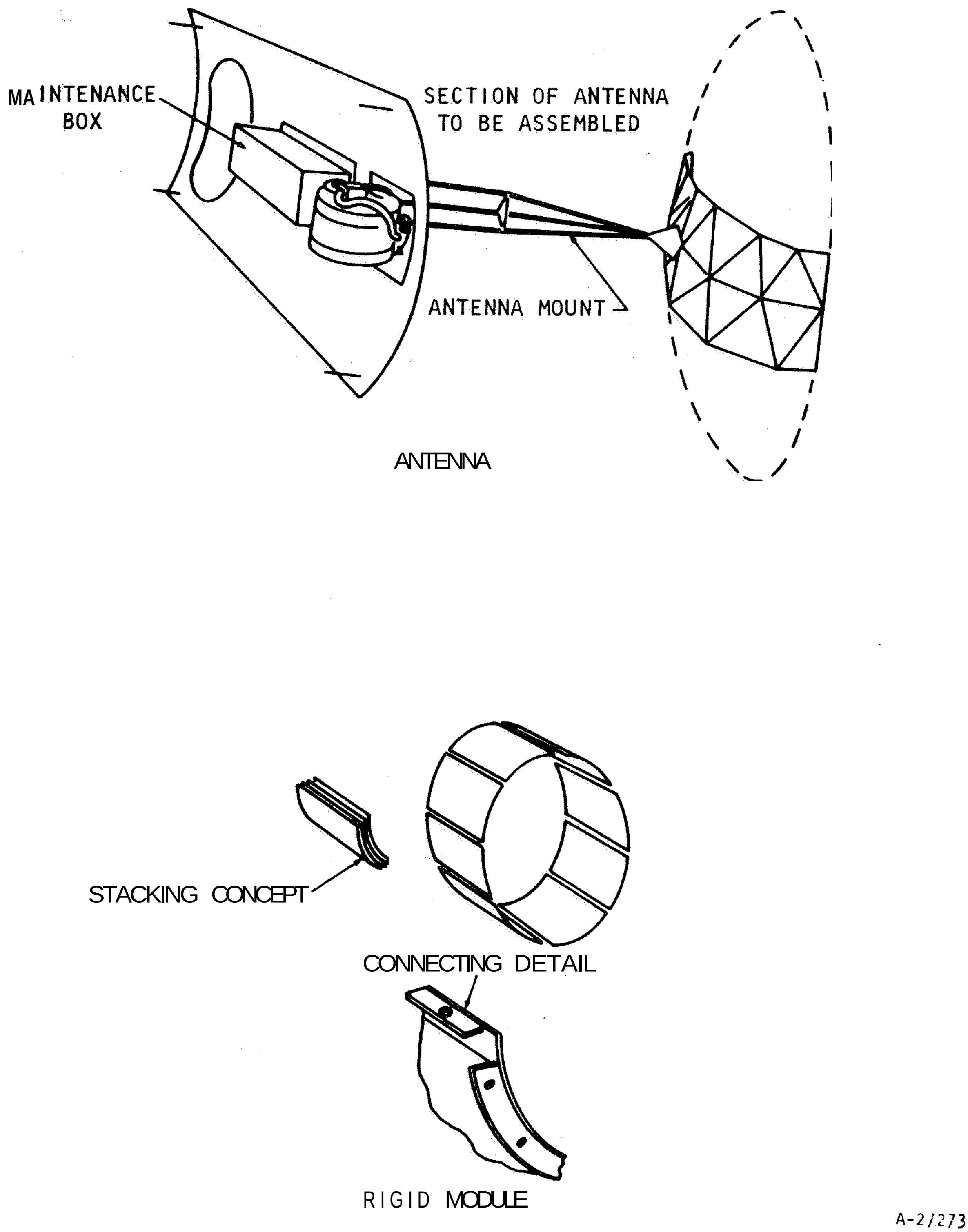


Figure 2-17. Antenna and Rigid Module Mockups for Neutral Buoyancy Tests

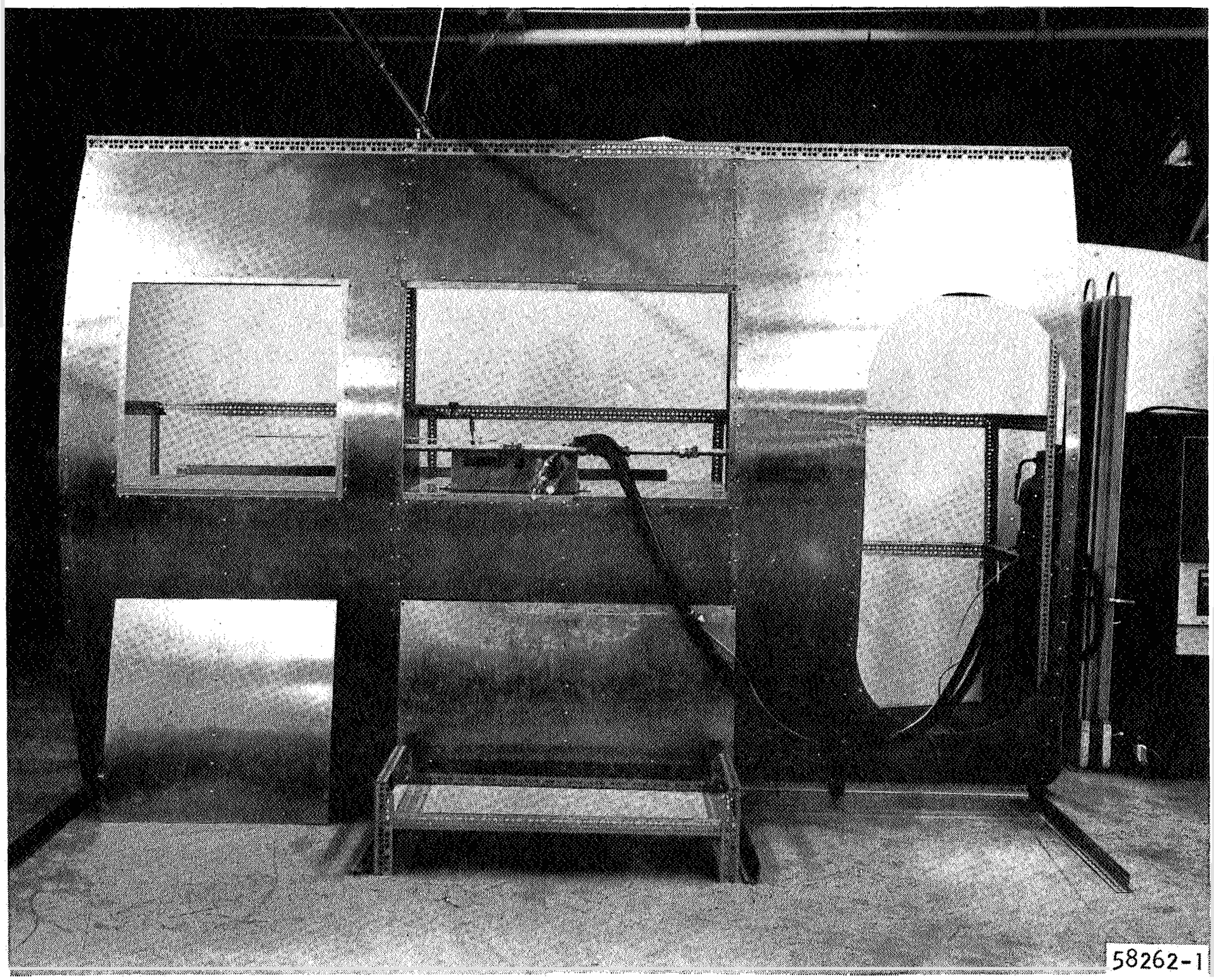


Figure 2-18. Spacecraft Mockup

Figure 2-19. Large **Inflatable Module**

bungee cords were hooked over a piece of dowling installed at the center of each joint of the antenna dish, and when attached at each joint, the panels were held in place.

The rigid module consisted of aluminum angles as a basic structure with hardware cloth simulating a structure 10 ft in diameter. Two sections, 10 ft in diameter, were assembled from eight panels each. These sections were then joined together. The sections were held in place on the space craft mockup with bungee cords. The joints consisted of a captive bolt and a basket nut on the mating angle.

The inflatable mockup consisted of two rings used for 15-man life rafts. These rings formed the ends of the structure and were spread with spreader bars to simulate an inflatable structure 10 ft in diameter and 10 ft long. One ring was secured to the maintenance mockup by lashing after inflation. Inflation was accomplished by filling with water from the pool pumping system.

Neutral buoyancy was achieved for most of the test hardware by Styrofoam blocks attached to segments and modules.

LOCOMOTION AIDS

The locomotion aids consisted of a rope tether, hand rail, rigid pole, taut rope, a ladder type, and a T-bar hand-hold type. The rope tether was fastened on the end of the space craft mockup away from the hatchway and was a 1/2-in.-diameter rope. The hand rail was a 1-in. diameter aluminum tube attached to a 4 in. standoff so that it extended from the hatchway to the opposite end and was approximately 4 in. below the access opening. This tubing was also used as a rigid pole by removing the standoff attachment away from the hatchway. One taut rope aid was accomplished by placing a 1/2 in. diameter rope between the two standoffs in place of the hand rail. A ladder-type and a T-bar hand-hold types of locomotion aids are illustrated in Figures 2-20 and 2-21. These were attached to the mockup in many positions for the various tasks. The T-bars were placed in a slotted boom that was attached below the maintenance access opening. This boom also served as a mounting structure for several restraint mechanisms.

RESTRAINTS

Several restraint systems were investigated during this program. Restraint mechanisms which were built and checked are illustrated in Figures 2-22 through 2-26. Several methods of connecting to the man and to the mockup were investigated; the results of these tests indicated that a rigid adjustable link (Figure 2-23) would best be used for the one-, two-, and three-leg restraints. These restraints were attached to the shell assembly through a universal attach locking. method as shown in

Figure 2-20. T-Bar Locomotion Aid With Foot Restraint Attached

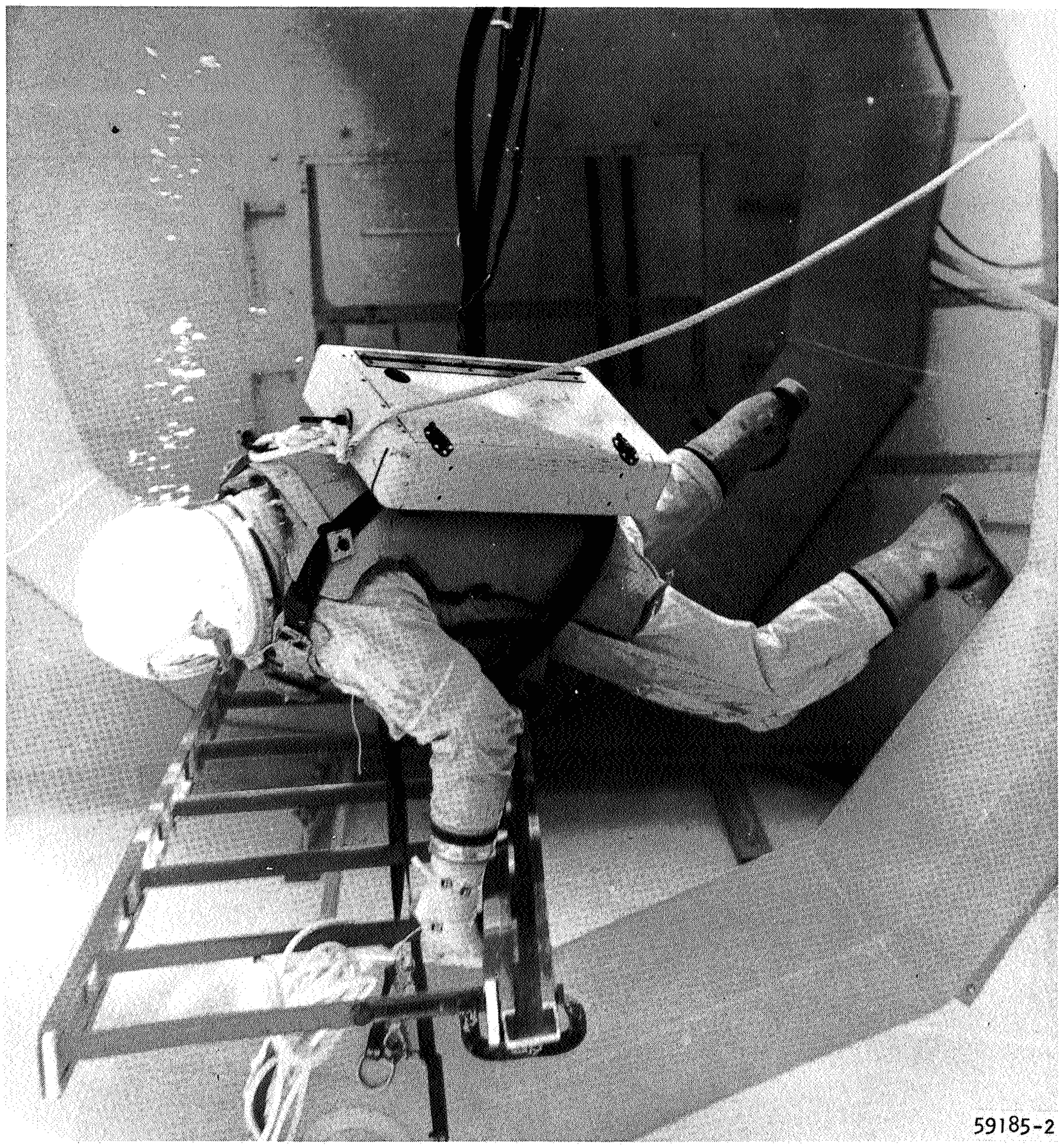
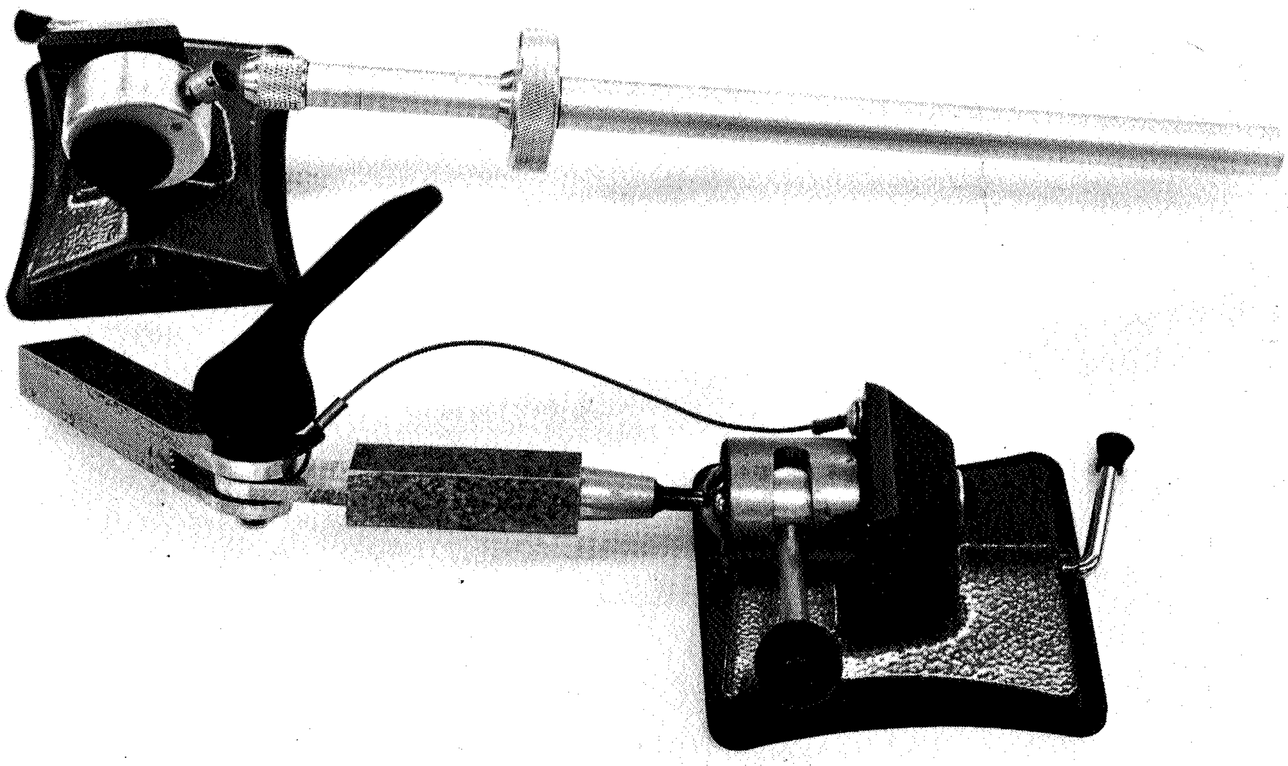
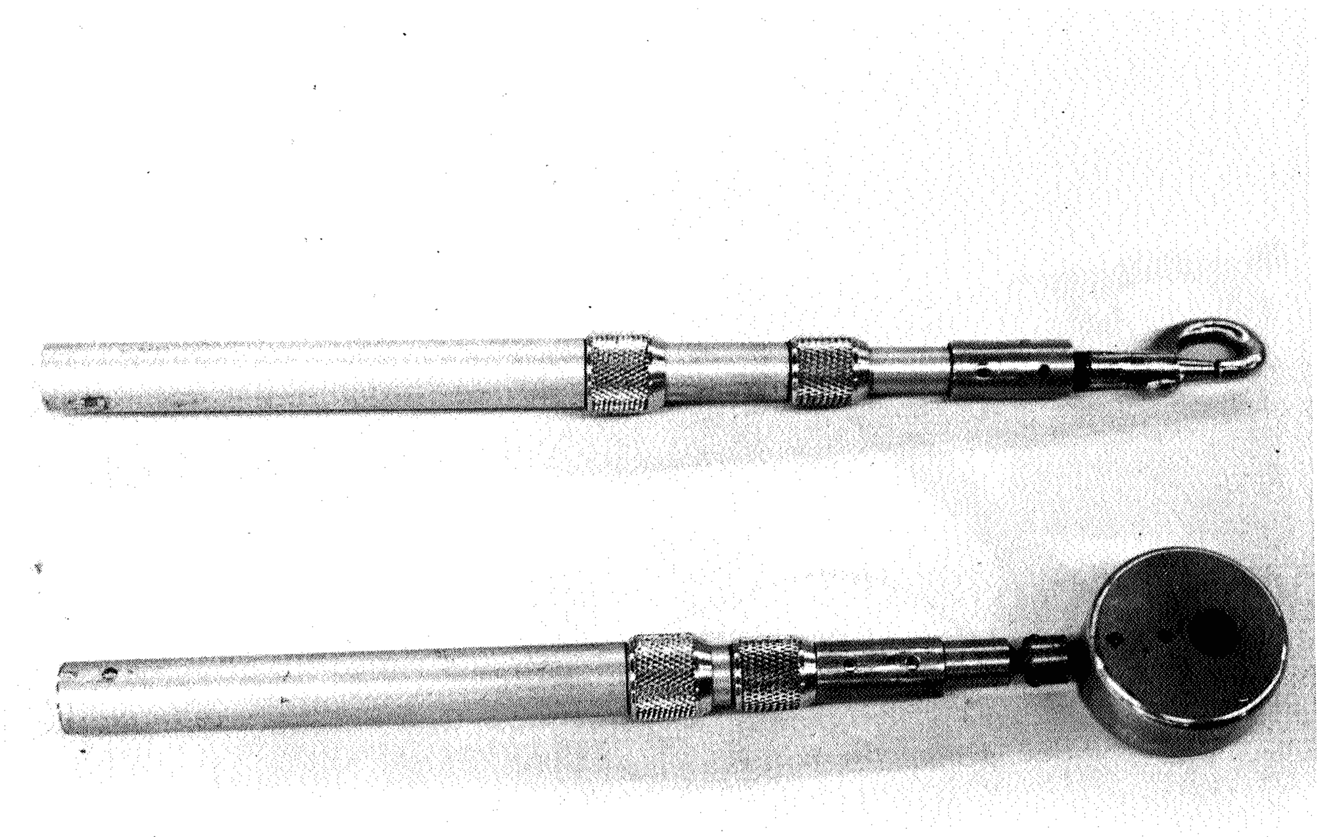


Figure 2-21. Ladder-Type Locomotion **Aid**



58551-9

Figure 2-22. Rigid Leg Restraint Concepts Tested and Found Inadequate



58551-1

Figure 2-23. Rigid Leg Restraint Design Concepts Used During Pressure-Suited Tests

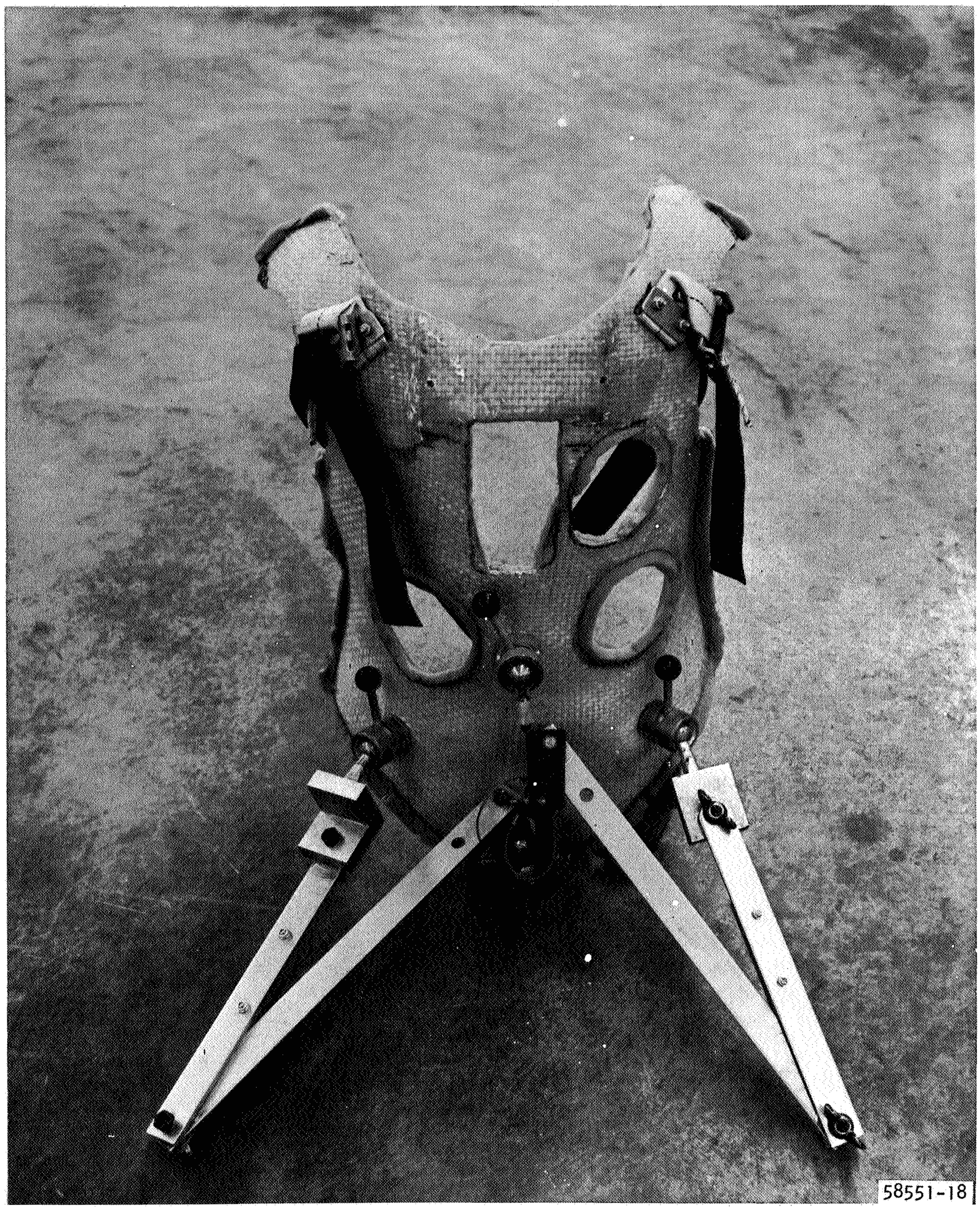


Figure 2-24. Universal Locking Mechanism Attached to Shell

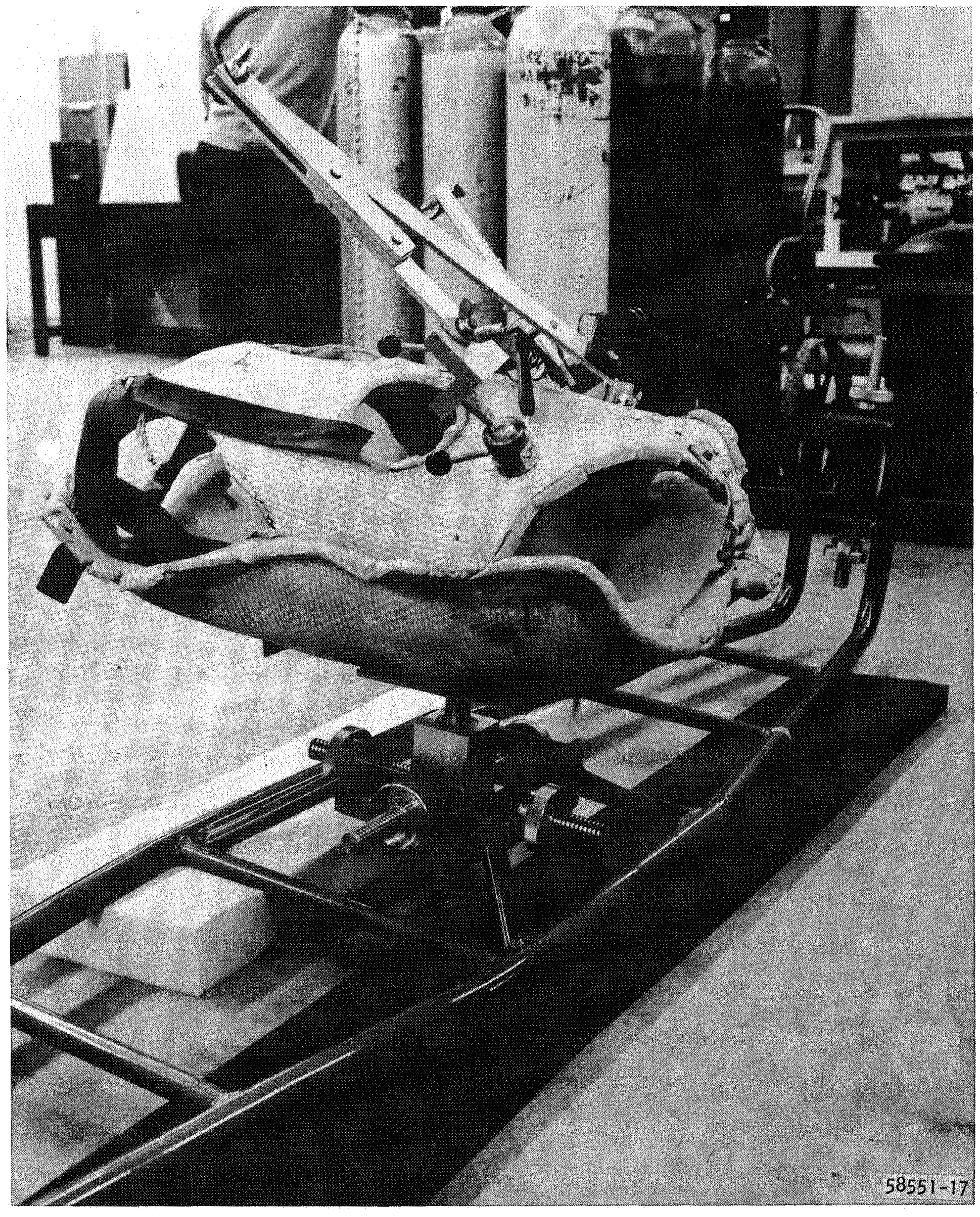


Figure 2-25. Universal Locking Mechanism Attached to Shell

Figure 2–26. Cage Restraint

Figures 2-24 and 2-25. The hook ending was attached to eyes mounted in the mockup with the attachment to the shell by the universal locking attachment. The single or double strap attachments (not illustrated) had the configuration of a lineman's waist belt. A cage restraint (Figure 2-26) was built, mounted on the boom, and tested. The foot restraint shown in Figure 2-29 consisted of a platform mounted on an adjustable attachment to the boom structure. Loops to restrain the feet were provided on the platform.

TOOLS

Off-the-shelf hand tools were selected as indicated by the type of fastener to be removed and the exertion or motion required by the subject to operate the tool. These requirements are discussed in the task definition and testing sections; no attempt will be made to distinguish these tools. Off-the-shelf and modified tools are shown in Figures 2-27 through 2-34. The tool holder used throughout the underwater testing (Figure 2-34) is constructed of sandwich synthetic foam supported by aluminum sheets. The off-the-shelf tools shown in Figures 2-27 through 2-30 were used as purchase because of problems encountered in attempting to modify them to neutral buoyancy. Modified tools shown in Figure 2-31 through 2-33 were readily modified to neutral buoyancy and to use by a subject with a pressure-suited glove. Initial attempts to increase handle size and to obtain neutral buoyancy were successful, but the material used would not stand up to wear or water immersion. Since this became a problem and all tools could not readily be modified for use, it was decided to modifythe remainingtools so that they would be readily usable by the pressure-suited subject. Table 2-1 lists tools by category and size.

FASTENERS

The fasteners used in this program were chosed according to the motions, forces, and sizes required, and according to the limitations of the pressure-suited subject. The fasteners used were readily available or readily modified to the tools to be used. Table 2-2 lists the fasteners by type and size, noting in each case the actual size of the fastener/tool interface.

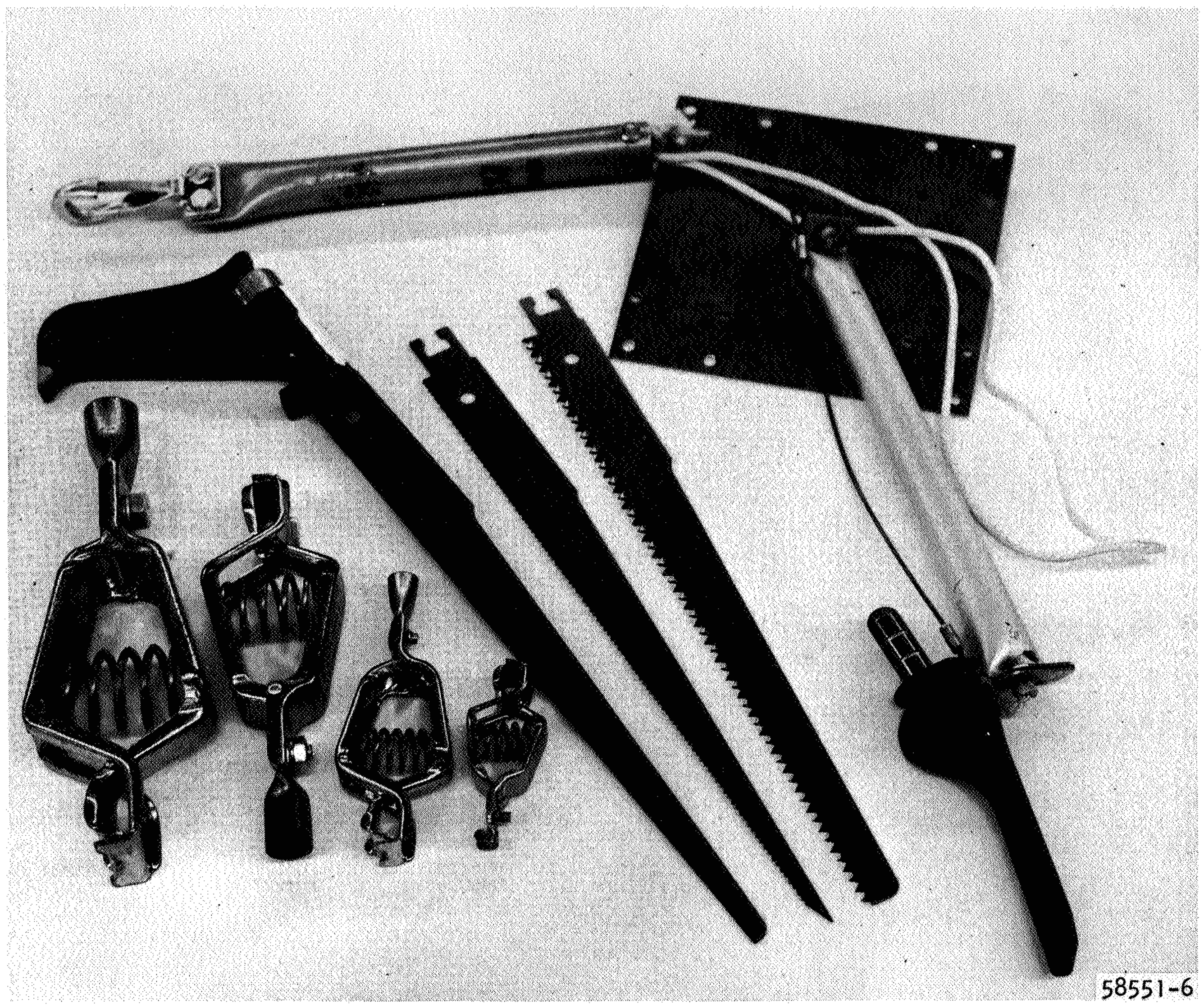


Figure 2-27. Off-the-shelf Tools Used in Maintenance Tests

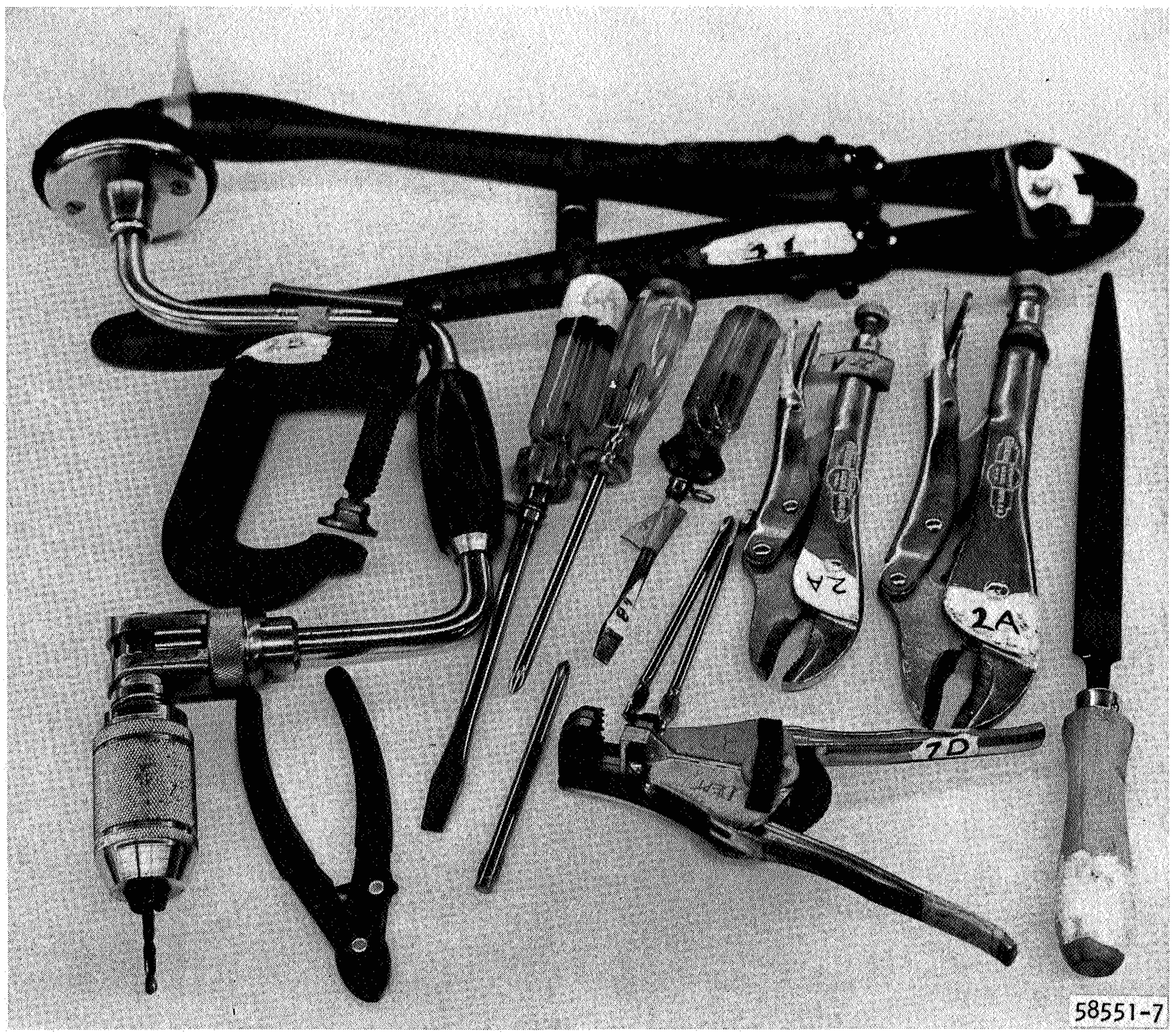
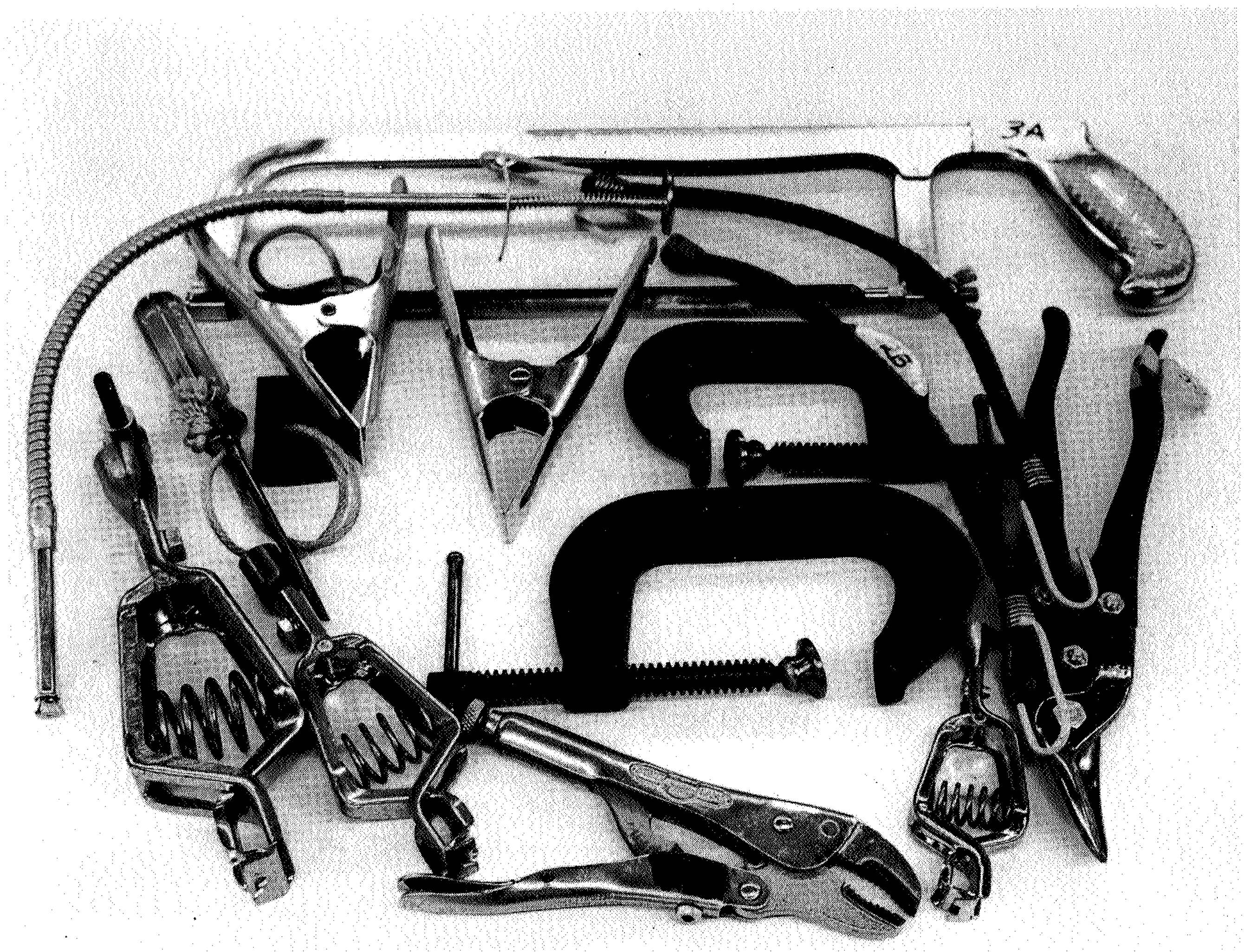


Figure 2-28. Off-the-shelf Tools Used in Maintenance Tests



58551-5

Figure *2-29.* **Off-the-shelf Tools** Used **in Maintenance Tests**

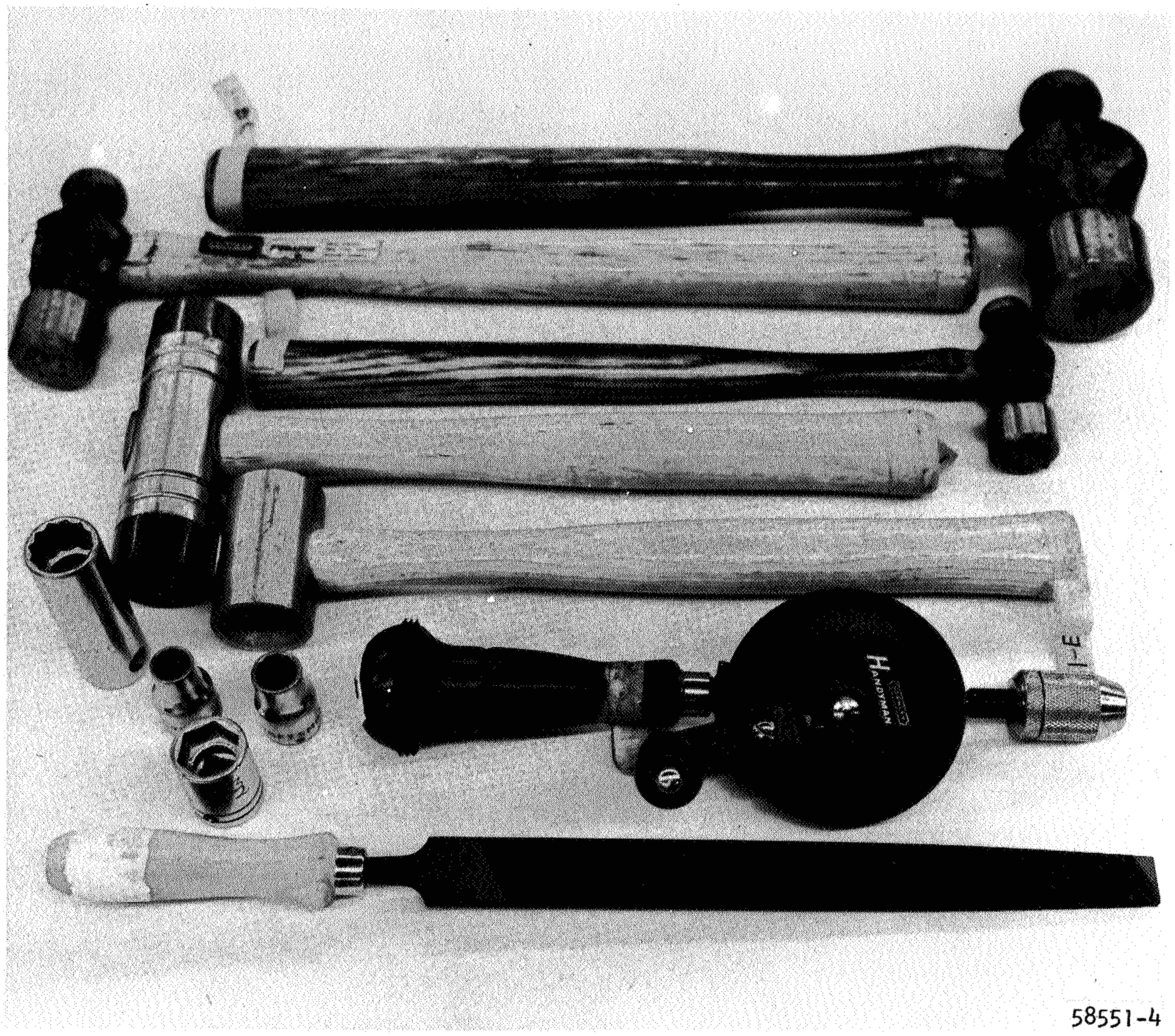


Figure 2-30. Off-the-shelf Tools Used in Maintenance Tests

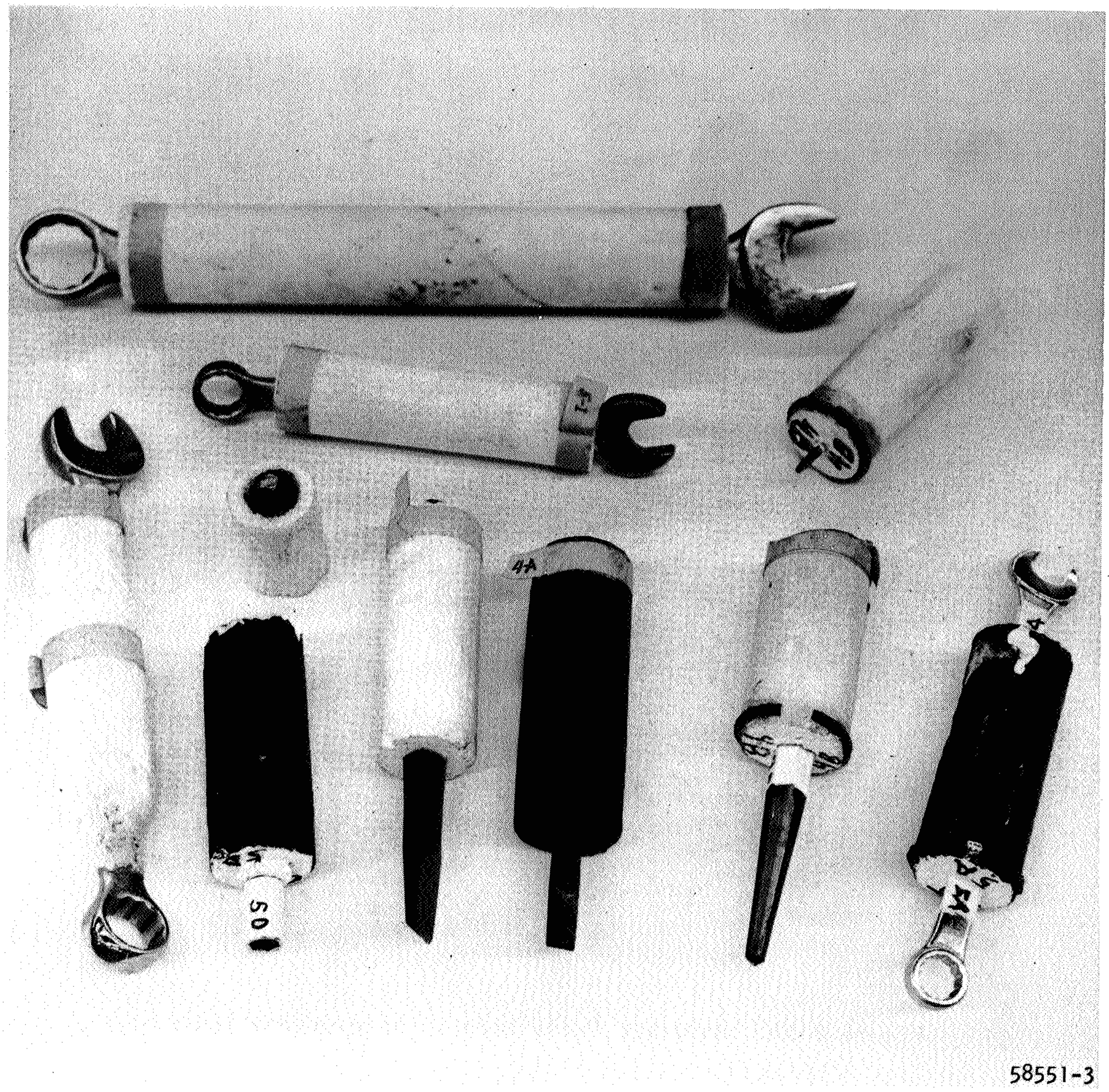


Figure 2-31. Modified Tools Used in Maintenance Tests

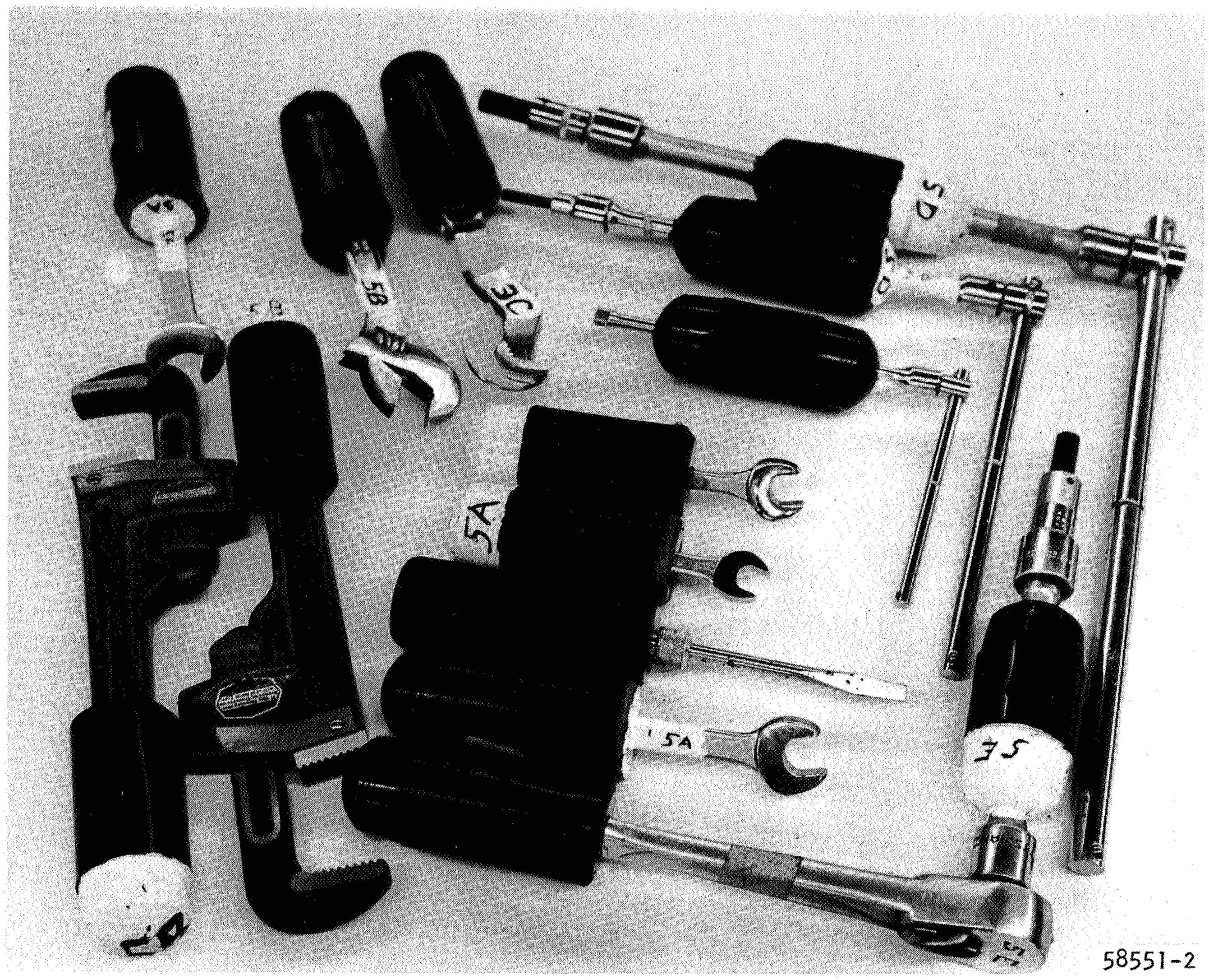


Figure 2-32. Modified Tools Used in Maintenance Tests

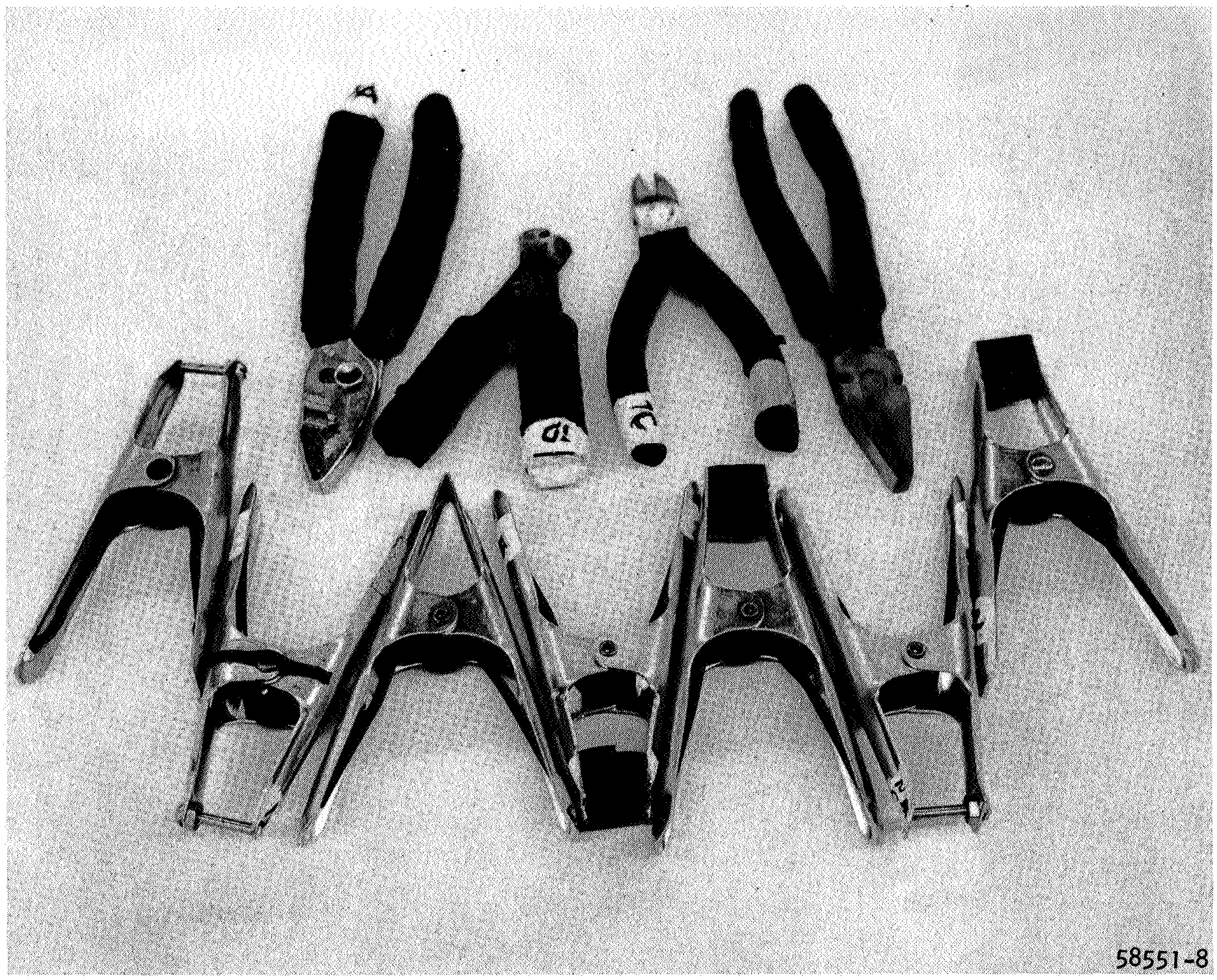


Figure 2-33. Modified Tools Used in Maintenance Tests

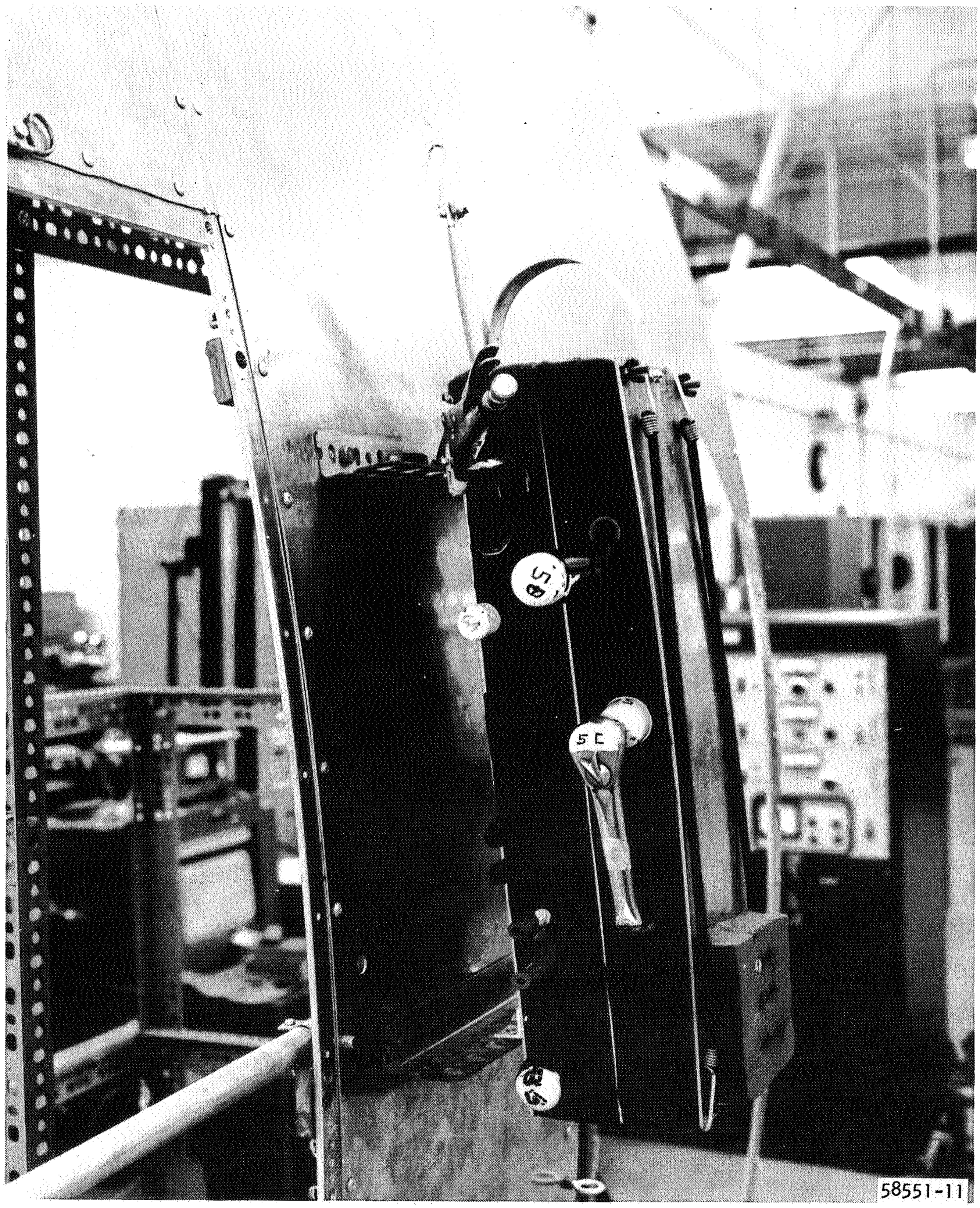


Figure 2-34. Foam Supported **Tool** Kit

TABLE 2-1

EVA TOOL DESCRIPTION CHART

Tool Category	Tool Code	A	B	C	D	E
Sparkproof ballpeen hammer	1	8-oz head 12-in. handle	24-oz head 15-in. handle	48-oz head 15-in. handle	--	--
Clamps	2	Vise grip wrench	C-clamp 13 in. and 4 in.	Hargrave improved spring clamp, 2-in. opening, 6-in. length	Spring clamp modified with rubber tips	Spring clamp modified with bolt sep. tips 1 in.
Saw	3	Hacksaw	Keyhole saw 4	Halfround metal file	--	--
Punch	4	Starting punch	Center punch	--	--	--
Wrench	5	Open end wrench	Open end adjustable	Self-adjusting lock wrench	T-handle with socket	Ratchet handle with socket
Screwdriver	6	4-in. blade length, 6/32-in. tip width	3-3/4-in. blade length 11/32-in. tip width	5-3/4-in. blade 15/32-in. tip width	--	--
Pliers	7	Combination pliers	Long-nose pliers	Diagonal cutting pliers	Stripmaster wire strippers	Clipper cut bolt clippers
Hand drill	8	Open ratchet bit brace	Hand drill --	--	--	--

TABLE 2-2

FASTENERS

Type	Large	Medium	Small
Internal wrenching	AN 565 A 820-16 (3/4-in. OD head) (3/8-in. ID head)	AN 565 A 524-12 (1/2-in. OD head) (1/4-in. ID head)	AN 565 A 428-12 (3/8-in. OD head) (3/16-in. ID head)
External wrenching	AN 8-11A (3/4-in. hex head)	AN 5-6A (9/16-in. hex head)	AN 4-5A (7/16-in. hex head)
Slotted*	AN 8-11A (3/4-in. hex head)	AN 5-6A (9/16-in. hex head)	AN 4-5A (7/16-in. hex head)

*Modified by machining a slotted head for screwdriver application.

SECTION 3

EXPERIMENTAL DESIGN
AND
TYPICAL TASK DESCRIPTIONS

DESIGN PHILOSOPHY

Because of the limited number of facts known about a pressure-suited man's capability to perform work in a zero-gravity environment, the program was designed to test a broad range of hardware variables. The program used one or two subjects and accepted some experimental contamination and poor reliability for the privilege of observing the positive and negative aspects of the large number of variables.

By testing the large number of different types of tools, restraints, locomotion aids, and fasteners, there was a resultant contamination of variables. It is believed, however, that the results of these tests make salient some of the most promising concepts for hardware and procedural solutions for applications in the weightless environment. These concepts should be tested later under more rigorous experimental conditions.

TEST CONDITIONS

The individual test conditions were obtained by combinations of variables along five dimensions: (1) simulation technique, (2) the type of task or its level of difficulty, (3) the locomotion aid employed, (4) the restraint device used, and (5) the tools used. These are not true or "clean" dimensions in the normal sense of dimension; however, they represent the categories necessary for organization of the tests.

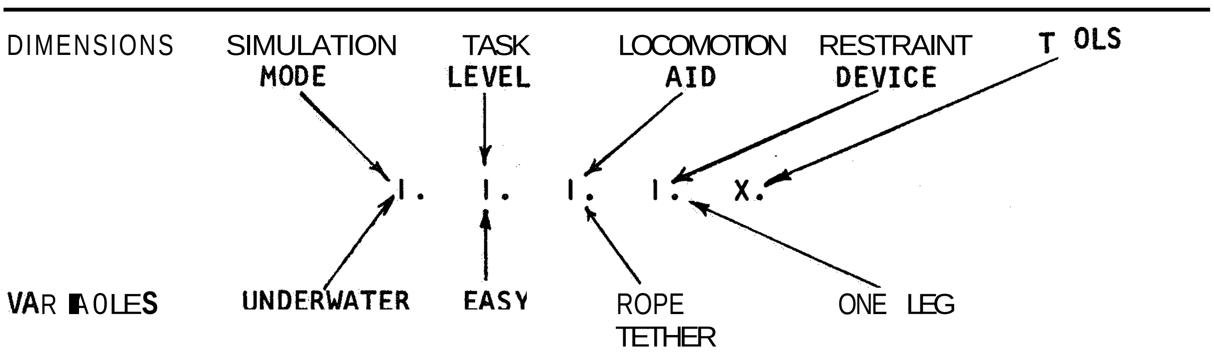
The variables manipulated during the study effort are summarized in Table 3-1. Three modes of simulation were used and are listed in the simulation mode column as follows: (1) underwater, (2) one-g, and (3) suspension. In the next column, titled "Task Level," are listed five types of tasks: (1) maintenance tasks, (2) assembly of beams, (3) assembly of panels, (4) assembly and erection of rigid modules, and (5) assembly and erection of inflatable modules. The maintenance task category identification is broken into three levels of maintenance task difficulty--easy, difficult, and hard--for the maintenance test portion of the study effort; the remaining four tasks are assembly of beams (antenna), folding panels (antenna fact), two rigid modules, and two inflatable modules for the large module erection test portion of the study. In the third column are listed the five locomotion aids used throughout the tests.
The rope tether, hand rail, hand hold, taut rope, and rigid pole were

TABLE 3-1
TEST VARIABLES

SIMULATION MODE	TASKS TYPE AND LEVEL	LOCOMOTION AID	RESTRAINT DEVICE	TOOLS
	Maintenance Tests			
1. Underwater	1. Easy	1. Rope tether	1. One Leg	1. Hammer
2. One-g	2. Difficult	2. Hand rail	2. Two Leg	2. Clamps
3. Suspension simulation	3. Hard	3. Hand hold	3. Three Leg	3. Saw
	Large Modules Erection Tests	4. Taut rope	4. Cage	4. Punch
	4 Beams (m se na)	5. Rigid pole (fixed one end only)	5. Foot With Strap Tether	5. Wrenches
				6. Screwdriver
	5. Folding panels (antenna face)		6. Gemini XII Type Straps	7. Pliers
	6. Two rigid modules			8. Hand Drill
	7. Two inflatable modules			

individually used in all three of the maintenance test levels and used individually or in combination during the erection of the large modules. The one-leg, two-leg, three-leg, cage foot with strap, and Gemini XII type of strap restraints listed in the fourth column were all used throughout the maintenance tests, but only the cage, foot, and Gemini XII type of strap restraints were used during the large module erection tests. In the "Tool Type" column are listed the eight types of tools that were used throughout testing. Two to 'five different representative tools of each tool type were tested.

Each listing in the columns of Table 3-1 is preceded by a number. These numbers were used in combination to identify the variables of each particular test. The consequence was a numerical code providing the numerous tests with individual identity. Only numbers from the first four columns were used in constructing the test codes. For example, the test code numbered 1.1.1.1.X. can be identified in the following manner.



A table containing the full test code and description is provided in Appendix A. It is recommended that this sheet be used for reference during the reading of the remaining sections.

The maintenance task tests are listed in Table 3-2. The simulation and task level code designations are in the left-hand columns, and the locomotion aid and restraint code designations across the top. The two test numbers at the bottom of the table represent the last tests conducted. The first of these, 1.3.3.6., was conducted to observe the advantages and disadvantages of a strap restraint system. The second listing was a maintenance test conducted using the six-degree-of-freedom simulator. For this test, tasks were selected from the easy, difficult, and hard task levels. The principal criteria for

TABLE 3-2

MAINTENANCE TESTS COMPLETED

		ONE LEG ROPE TETHER XX1.1.	TWO LEG HAND RAIL XX2.2.	THREE LEG HAND HOLD XX3.3.	CAGE TAUT ROPE XX4.4.	FOOT RIGID POLE XX5.5.
UNDERWATER SUITED	1.1.XX easy	COMPLETED	POOR NEUT. BUOYANCY	COMPLETED	COMPLETED	COMPLETED
	1.2.XX difficult	POOR NEUT.	DELETED	DELETED	COMPLETED	COMPLETED
	1.3.XX hard	COMPLETED	COMPLETED	COMPLETED	COMPLETED	COMPLETED
FULL GRAVITY UNSUITED	2.1.XX easy 2 subjects	NO LOCOMOTION COMPLETED	AID(XX0.2)-COMPLETED	NOT SCHEDULED	NOT SCHEDULED	NOT SCHEDULED
	2.2.XX difficult	COMPLETED 2 SUBJECTS	COMPLETED	NOT SCHEDULED	NOT SCHEDULED	NOT SCHEDULED
	2.3.XX hard 2 subjects	COMPLETED	COMPLETED	NOT SCHEDULED	NOT SCHEDULED	NOT SCHEDULED
FULL GRAVITY SUITED	2.1.XX easy	COMPLETED	COMPLETED	NOT SCHEDULED	NOT SCHEDULED	NOT SCHEDULED
	2.2.XX difficult	COMPLETED	COMPLETED	NOT SCHEDULED	NOT SCHEDULED	NOT SCHEDULED
	2.3.XX hard	COMPLETED	COMPLETED	NOT SCHEDULED	NOT SCHEDULED	NOT SCHEDULED

1.3.3.6 - UNDERWATER, HARD, HAND HOLD, STRAP RESTRAINT

(3.1.0.6, 3.2.0.6, 3.3.0.6) - SIX DEGREE OF FREEDOM, EASY-DIFFICULT-HARD COMPOSITE, NO LOCOMOTION AID, STRAP RESTRAINT (SEE TABLE A-1) task selection from the three levels were uniqueness and feasibility of accomplishment. The *XX3.3*, *XX4.4*, and *XX5.5* series were not scheduled for the suited and unsuited full-gravity conditions for the following reasons.

a. The third leg of the three-leg restraint configuration was to provide additional stability by the weight on his feet.

b. The cage restraint was not tested because it offered no real restraint in the full-gravity condition. It was assumed that if the subject could perform the tasks standing in front of the maintenance mockup, the addition of a large cage device around him, which offered enough room to get from one position to another, would not affect his performance.

c. The foot restraint was not tested in the full-gravity condition for reasons of safety. It was very difficult for the subject to work in the suit when it was pressurized. Whenever the subject lost his balance, he was able to regain his balance by repositioning his feet. It was hypothesized that the restraining of the feet would remove this compensating ability and therefore should not be done.

In the full-gravity unsuited tests, all maintenance tests but *2.2.2.2.* were conducted on two separate occasions using two different subjects. All other tests were conducted with one subject.

Tests 1.2.1.1. and 1.1.2.2. were partially completed due to the subject's fatigue. Fatigue resulted from the constant energy expended in attempting to get and maintain a good work position while being slightly negative in buoyancy. Tests 1.2.2.2., 1.2.3.3., and 1.3.3.3. were deleted because it was concluded that the rigid-leg restraint design was inadequate. In all previous two-and three-rigid-leg restraint tests, the subject had broken some or all of the restraints in attempting to find a position from which he could perform the tasks. The locomotion aids and restraints used during the large module tests are delineated in Table 3-3. The rigid-leg restraints were not used in the large module tests because they had been observed to be inadequate during the conduction of the maintenance tests.

The test order is shown in Table *3-4.* The maintenance tests were scheduled to be completed before the large modules tests, and the order of tesing, listed by simulation mode, was full-gravity unsuited, full-gravity suited, underwater, and suspension simulation.

TABLE 3-3

TEST HARDWARE CONFIGURATIONS FOR LARGE MODULE ASSEMBLY

CATEGORY	TYPE	TESTS			
		ANTENNA BEAMS	ANTENNA FACE	RIGID MODULES	INFLATABLE MODULES
LOCOMOTION AIDS	Rope Tether	X	X		X
	Hand Rail	X	X	X	
	Hand Hold	X	X		X
	Taut Rope	X	X	X	
	Rigid Pole	X	X	X	X
RESTRAINTS	Cage	X	X	X	
	Foot-Strap	X	X		
	Window Washer Straps	X	X	X	X

(X = variables included in test)

TABLE 3-4

TEST SEQUENCE

Test Sequence	Test Code	Test Sequence	Test Code	Test Sequence	Test Code
1	2.1.0.1.G	28	1.3.5.5.	55	1.5.5.3
2	2.1.0.1.R	29	1.1.3.3.	56	1.5.1.6.
3	2.1.0.2.G	30	1.3.3.6.	57	1.5.2.6.
4	2.1.0.2.R	31	1.4.1.4.	58	1.5.3.6.
5	2.2.0.1.G	32	1.4.2.4	59	1.5.4.6.
6	2.2.0.1.R	33	1.4.3.4.	60	1.5.5.6.
7	2.2.0.2.R	34	1.4.4.4.	61	1.6.2.5
8	2.3.0.1.G	35	1.4.5.4.	62	1.6.3.5
9	2.3.0.1.R	36	1.4.1.5.	63	1.6.4.5.
10	2.3.0.2.G	37	1.4.2.5.	64	1.6.2.4.
11	2.3.0.2.R	38	1.4.3.5.	65	1.6.3.4.
12	2.1.0.1.	39	1.4.4.5.	66	1.6.4.4.
13	2.1.0.2	40	1.4.5.5.	67	1.6.2.3.
14	2.2.0.1.	41	1.4.1.6.	68	1.6.3.3.
15	2.2.0.2.	42	1.4.2.6.	69	1.6.4.3.
16	2.3.0.1.	43	1.4.3.6.	70	1.6.2.6.
17	2.3.0.2.	44	1.4.4.6.	71	1.6.3.6.
18	1.2.1.1.	45	1.4.5.6.	72	1.6.4.6.
19	1.1.2.2.	46	1.5.1.4.	73	1.7.1.5.
20	1.3.1.1.	47	1.5.2.4.	74	1.7.3.5.
21	1.3.2.2.	48	1.5.3.4.	75	1.7.1.6.
22	1.1.1.1.	49	1.5.4.4.	76	1.7.3.6.
23	1.1.4.4.	50	1.5.5.4.	77	3.1.0.6.
24	1.2.4.4.	51	1.5.1.3.	78	3.2.0.6.
25	1.3.4.4.	52	1.5.2.3.	79	3.3.0.6.
26	1.1.5.5.	53	1.5.3.3.	80	3.4.0.6.
27	1.2.5.5.	54	1.5.4.3.	81	3.5.0.6.

See Table A-1 for test code description.

Beginning with task level 1. (easy), and progressing through task level 2. (difficult) and 3. (hard), the tasks varied in terms of the projected ability to tax the subject's capability to perform the task. Alterations in the basic hardware and performance requirements for each task level were accomplished along two dimensions. The first dimension was that of dexterity; each task level had increasing demands on the subject's ability to manipulate finer and smaller items, including both tools and hardware. The second dimension was that of force; each task level required greater force application with an increasing variety of equipment and tools. The task sequences for the easy, difficult, and hard levels are presented in the typical data collection sheets of Table 3-5 (easy), 3-6 (difficult), 3-7 (hard), and 3-8 (task composite for six-degree-of-freedom simulation test). A detailed description of each task sequence is presented in Table 3-9. In this table the task is identified, the start and stop time is indicated as related to task segment, and the overall task description is provided.

Detailed procedures for the erect'ion of the large modules were not constructed, however, a set of general procedures was prepared. The test philosophy for the large module tests was to allow the subject freedom to perform the module assemblies as he deemed appropriate. It was believed that the subject would be provided adequate information from the actual work situation to accomplish the assembly goals.

The antenna beam assembly test was begun with the boom and locomotion aids in position. The maintenance boom was positioned at the beginning of the test directly below the antenna boom. The test subject had to reposition the maintenance boom twice during the test. At each re-positioning, the restraint mode was changed by the diver. The antenna beams and joints were contained in three packages. The first package was made up of six joints and sixteen antenna beams, while the second and the third packages contained six joints and twelve antenna beams. Once he was positioned at the work station, the subject pulled the package to him on a taut line. He then assembled a part of the antenna using the beams and joints of that particular package, repositioned the maintenance boom, procured the second package, assembled the beams and joints of that package, repositioned the boom, procured the last package, and completed assembling the antenna. The general procedures for the antenna assembly are listed in the data collection sheets of Table 3-10.

Following the assembly of the antenna, a panel facing was installed on the antenna framework. The panels were folded and connected four to a package, except the sixth and last package, which had two panels. Locomotion aids were set up in the same combination as that for the beam assembly test (see Table 3-3). Once positioned at his work station, the subject pulled the packages to him, two at a time. One of the two

TABLE 3-5

DATA SHEET FOR TYPICAL EASY MAINTENANCE TEST

TEST NO. 1122	DATE:	SUBJECT:	OBSERVER:	
TASK NO.	TASK TIME	**TASK SEQUENCE**	**EQUIPMENT**	**REMARKS**
1.		Exit hatch and traverse to spacecraft mockup work station. Snap tool kit to spacecraft mockup. Hand on Restraint	Sandwich tool kit and handrail	
2.		Engage restraint. Hand on Tool Kit	Two leg restraint	
3.		Fasten tool kit. Hand on Tool Used to Remove Access Panel	Two 3-in. C-clamps	
4.		Procure tool from tool kit and disengage 4 fasteners holding access panel. Replace tool in kit. Hand on Clamp	Socket T-handle with 3/8 Allen head 1/2 in. drive	
5.		Obtain clamp, remove access panel, and clamp to spacecraft mockup, out of way. Hand on Pliers	Vise-grip	

TABLE 3-5 (Continued)

TEST NO. 1122	DATE:	SUBJECT:	OBSERVER:	
TASK NO.	TASK TIME	TASK SEQUENCE	EQUIPMENT	REMARKS
6.		Procure wire cutters from tool kit and cut wire on maintenance box. Return pliers to tool kit. Hand Off Cutters	Side cutter	
7.		Turn valve off on tube connection to maintenance box. Procure wrench. Hand Contact with Wrench		
8.		Disengage tube connection at maintenance box. Replace wrench. Hand Off Wrench	Crescent wrench	
9.		Procure wrench and disengage 2 bolts holding maintenance box to spacecraft mockup. Return wrench to tool kit. Hand Off Wrench	Socket ratchet 1/2-in. drive with 3/8-in. Allen head.	
10.		Procure clamp and remove maintenance box; place and clamp on spacecraft mockup. exterior. First Movement of Test Subject to Panel	Stick lanyard	

TABLE 3-5 (Continued)

TEST NO. 1122	DATE:	SUBJECT:	OBSERVER:	
TASK NO.	TASK TIME	TASK SEQUENCE	EQUIPMENT	REMARKS
11.		Release clamp pressure holding access panel to spacecraft mockup; remove panel position access panel in opening. <u>Positioning of First Fastener in Panel for Finger Tightening</u>		
12.		Finger tighten bolts of access panel. Return clamp to tool kit. <u>Hand on Tool in Kit</u>		
13.		Procure wrench and tighten access door bolts (4). Return wrench to kit. <u>Tool Contact with Kit</u>	Socket T handle with 1/2-in. drive with 3/8-in. Allen head.	
14.		Release maintenance box from spacecraft mockup exterior and secure to test subject by lanyard. <u>Hand on Restraint Connector to Mockup</u>		
15.		With maintenance box in hand disengage restraint. <u>Visual Separation of Restraint</u>		

TABLE 3-5 (Continued)

TEST NO. 1122 DATE: SUBJECT: OBSERVER:

	TASK TIME	TASK SEQUENCE	EQUIPMENT	REMARKS
4		Traverse with maintenance box through hatch. <u>Last Body Segment to Clear Hatch</u>		

TABLE 3-6

DATA SHEET FOR TYPICAL DIFFICULT MAINTENANCE TEST

TEST NO. 1233 DATE: SUBJECT; OBSERVER:

TASK NO.	TASK TIME	TASK SEQUENCE	EQUIPMENT	REMARKS
1.		Exit hatch and traverse to spacecraft mockup work station. Snap tool kit to spacecraft mockup. Hand on Restraint	Sandwich tool kit and hand hold locomotion aid	
2.		Engage restraint. Hand on Tool Kit	Three leg restraint	
3.		DELETED		
4.		Procure tool from tool kit and disengage 4 fasteners holding access panel. Replace tool in kit. Hand on Clamp	Socket ratchet 3/8 in. drive 7/32 Allen head Med. Allen head bolts	
5.		Obtain clamp remove access panel and clamp to spacecraft mockup; out of the way. Hand on Valve	Vise-grip	

TABLE 3-6 (Continued)

TEST NO. 1233	DATE:	SUBJECT:	OBSERVER:	
TASK NO.	**TASK TIME**	**TASK SEQUENCE**	**EQUIPMENT**	**REMARKS**
6.		Turn off valve to tubing; procure two wrenches. <u>First Contact of Wrench to Connector</u>	Open end **9/16** in. and **11/16** in.	
7.		Disengage tubing to maintenance box at union; return wrenches to tool kit. <u>Hand Touches Hammer in Tool Kit</u>	Open end **9/16** in. and **11/16** in.	
8.		Procure punch and hammer. Punch rivet on top of box to center reamer. Return hammer and punch to kit. <u>Hand on Brace</u>	Center punch and hammer (large).	
9.		Procure brace and bit and drill out rivet on top of maintenance box. Return brace to kit. <u>Hand on Hammer</u>	Hand drill with No. **27** drill.	

TABLE 3-6 (Continued)

TEST NO. 1233	DATE:	SUBJECT:	OBSERVER:	
TASK NO.	TASK TIME	TASK SEQUENCE	EQUIPMENT	REMARKS
10.		Procure hammer and punch, and punch rivet free. Replace hammer and punch in kit. Hand on Screwdriver (For next task)	Drift punch and Hammer (large)	
11.		Procure screw driver; remove screws securing top of maintenance box. Remove top of maintenance box. Procure clamp from kit and secure top to spacecraft mockup. Hand on Wire Cutters (Hanging on Wrist)	Screwdriver Spring clamp (bolt tongue)	
12.		Procure wire cutters. Cut two wires to switch in maintenance box. Return pliers to tool kit. Hand on Screw Driver	Pliers	
13.		Disengage screws and remove switch from maintenance box. Place removed switch in tool kit and procure new switch. Release of Switch No. 2 from Kit	Screwdriver on wrist lanyard	

TABLE 3-6 (Continued)

TEST NO. 1233	DATE:	SUBJECT:	OBSERVER:	
TASK NO.	**TASK TIME**	**TASK SEQUENCE**	**EQUIPMENT**	**REMARKS**
14.		Position new switch in place, tighten screws. <u>Hand Touching Pliers in Tool Kit (For Next Task)</u>		
15.		Procure wire strippers and strip one inch of insulation from wires to switch. Return strippers to kit. <u>Hand Free of Wire Strippers</u>	Wire strippers	
16.		Procure pointed pliers and make loop on wires and place under screws on switch. Return pliers to tool kit. <u>Hand Free of Pliers</u>	Pointed pliers	
17.		Tighten screws on switch to secure wires to switch. Return screwdriver to kit. <u>Hand Free of Screwdriver</u>		

TABLE 3-7

DATA SHEET FOR TYPICAL HARD MAINTENANCE TEST

TEST NO. 1333		DATE:	SUBJECT: OBSERVER:	
TASK NO.	TASK TIME	TASK SEQUENCE	EQUIPMENT	REMARKS
1.		Exit hatch and traverse to spacecraft mockup work station. Snap tool kit to spacecraft mockup. Hand on Restraint	Sandwich tool kit and hand hold locomotion aid.	
2.		Engage restraint. Hand on Tool Kit	Three leg restraint	
3. DELETE		Fasten tool kit to spacecraft mockup. Hand on Tool Used to Remove Access Panel	Two vise grips	
4.		Procure tool from tool kit and disengage two fasteners holding access panel. Replace tool in kit. Hand on Clamp	Screwdriver (large)	
5.		Obtain clamp. Remove access panel and clamp to spacecraft mockup out of way. Hand on Wrench Used in Next Task	Lanyard (stick/rope)	

TABLE 3-7 (Continued)

TEST NO. 1333	DATE:	SUBJECT:	OBSERVER:	
TASK NO.	**TASK TIME**	**TASK SEQUENCE**	**EQUIPMENT**	**REMARKS**
6.		Procure two wrenches from kit and disengage two unions on pipe in front of maintenance box. Replace wrenches in tool kit. First Wrench to Touch Tool Kit	Two 10 in. pipe wrenches 50 ft/lbs torque	
7.		Remove pipe segments and place in tool kit. Pipe Segment Contained in Kit		
8.		Procure wrench and screwdriver from kit. With screwdriver remove two wires from terminal board, place on by-pass connector and tighten nuts with wrench. Replace wrench and screwdriver. Hand on File Used in Next Task	Small screwdriver and spintight wrench 11/32 in.	
9.		Procure file from tool kit and file notch on bar holding black box. Return file to tool kit. Hand on Tool for Next Task	File	

TABLE 3-7 (Continued)

TEST NO. 1333	DATE:	SUBJECT:	OBSERVER:	
TASK NO.	TASK TIME	TASK SEQUENCE	EQUIPMENT	REMARKS
10.		Procure saw and cut bar on notch. Return saw to tool kit. Hand on Tool for Next Task	Hacksaw	
11.		Procure bolt cutters and cut rod securing maintenance box. Return cutter to tool kit. Hand on Tool for Next Task	Bolt cutters	
12.		Procure wrench and remove bolts holding maintenance box to spacecraft mockup. Replace wrench in tool kit. Hand on Lanyard	Screwdriver (large) Small slotted head bolts	
13.		Release maintenance box from spacecraft mockup; secure to subject with lanyard. Hand on Restraint Connector to Mockup	Stick lanyard	
14.		With maintenance box in hand release restraint. Visual Separation of Restraint		

TABLE 3-7 (Continued)

TEST NO. 1333		DATE:	SUBJECT:	OBSERVER:
TASK NO.	TASK TIME	TASK SEQUENCE	EQUIPMENT	REMARKS
15.		Traverse with maintenance box in hand to hatch area. <u>Last Body Segment to Clear Hatch</u>		

TABLE 3-8

DATA SHEET FOR SUSPENSION SIMULATION

TASK COMPOSITE MAINTENANCE TEST

TEST NO: SUSPENSION SIMULATION		DATE:	SUBJECT:	OBSERVER:
TASK NO.	**TASK TIME**	**TASK SEQUENCE**	**EQUIPMENT**	**REMARKS**
1.		Traverse to spacecraft mockup access opening. Hand on Restraint	Rope tether	Tool kit in place.
2.		Engage restraint. Hand on Wrench	Single strap	If eye bolts are used, strap will need modification.
3.		Procure wrench from tool kit and disengage four bolts on access panel. Replace wrench in kit. Hand Free of Wrench	Socket ratchet 3/4 in. head for hex. bolts.	
4.		NOTE: Panel will be taken from opening and stowed by a member of the test team.		
5.		Procure two pipe wrenches from kit and disengage two unions on pipe in front of maintenance box. Replace wrenches in tool kit. Hand Free of Second Wrench in Tool Kit	Two 10 in. pipe wrenches	

TABLE 3-8 (Continued)

TEST NO. SUSPENSION SIMULATION		DATE:	SUBJECT:	OBSERVER:
TASK NO.	TASK TIME	TASK SEQUENCE	**EQUIPMENT**	REMARKS:
6.		Unscrew pipe unions and remove pipe. Place pipe in tool kit. Pipe Contained in Kit		
7.		Procure wrench and screw-driver from kit. With screwdriver, remove two wires from terminal board, place on by-pass connector and tighten nuts with wrench. Replace tools in kit. Hand on File	Screwdriver (small) 11/32 in. spintight wrench	
8.		Procure file from tool kit and file notch on bar. Return file to tool kit. Hand on Bolt Cutters	File	
9.		Procure saw and cut bar on hatch. Return saw to tool kit. Hand on Bolt Cutters	Saw	

TABLE 3-8 (Continued)

TEST NO. SUSPENSION SIMULATION		DATE:	SUBJECT:	OBSERVER:
TASK NO.	**TASK TIME**	**TASK SEQUENCE**	**EQUIPMENT**	**REMARKS**
10.		Procure bolt cutters and cut rod. Return bolt cutters to kit. <u>Hand on Valve</u>	Bolt cutters	
11.		Turn valve off on copper tubing. <u>Hand on First Wrench in Kit</u>		
12.		Procure two open end wrenches and disengage tubing to maintenance box at union. Return wrenches to tool kit. <u>Hand on Hammer</u>		
13.		Procure punch and hammer and punch rivet on top of maintenance box. Return hammer and punch to kit. <u>Hand on Hand Drill</u>		

TABLE 3-8 (Continued)

EST NO. SUSPENSION SIMULATION	DATE:	SUBJECT:	OBSERVER:	
ASK 0.	TASK TIME	TASK SEQUENCE	EQUIPMENT	REMARKS
4.		Procure hand drill and drill out rivet on top of maintenance box. Return hand drill to tool kit. Hand on Hammer	Hand drill with no. 27 drill	
5.		Procure hammer and and punch rivet free. Return hammer and punch to tool kit. Hand on Wire Cutters	Hammer and drift punch	
16.		Procure wire cutters and cut two wires to switch on maintenance box. Return cutters to tool kit. Hand on Screwdriver	Wire cutters	
17.		Procure screwdriver and remove switch from from top of maintenance box. Place removed switch in tool kit, and procure new switch. Release of Switch no. 2 from Kit	Screwdriver w/ wrist lanyard	

TABLE 3-8 (Continued)

TEST NO. SUSPENSION SIMULATION		DATE:	SUBJECT:	OBSERVER:
TASK NO.	TASK TIME	TASK SEQUENCE	EQUIPMENT	REMARKS
18.		Position new switch in place and tighten screws. <u>Hand on Wire Strippers</u>		
19.		Procure wire strippers and stip one inch of insulation from wires to switch. Return strippers to tool kit. <u>Hand on Pliers</u>	Wire strippers	
20.		Procure pointed pliers and make loop on wires and place under screws on switch. Return pliers to tool kit. <u>Hand Free of Pliers</u>	Pointed pliers	
21.		Tighten screws on switch to secure wires to switch. Return screwdriver to tool kit.		
		NOTE: If time allows, the test may continue: (have team member replace access panel in the opening.:)		

TABLE 3-8 (Continued)

TEST NO. SUSPENSION SIMULATION		DATE:	SUBJECT:	OBSERVER:
TASK NO.	TASK TIME	TASK SEQUENCE	EQUIPMENT	REMARKS
22.	DELETED	Procure wrench and replace four bolts in the access panel. Return wrench to kit.	Socket T handle with Allen head (large)	

TABLE 3-9

MAINTENANCE TASK DESCRIPTIONS

DESCRIPTIONS

1. Traverse to Spacecraft Mockup With Tool Kit and Attach

(Full gravity tests and 1211 and 1122), (start time-start test command; stop time-hand on restraint)--Move from hatch to work station with tool kit in one hand and use other hand to apply forces necessary for locomotion. Upon arrival at work station, attach tool kit to maintenance mockup with one hand by pushing spring steel hook snap against angle iron rib until it snaps into hole.

2. ·aver to Spacecraft Mockup

(Underwater tests except 1211 and 1122), (start time-start test command; stop time-hand on restraint)--Move from hatch to work station using both hands to apply forces necessary for locomotion.

3. Engage Restraint

(Start time-hand on restraint; stop time-hand on tool kit (full gravity tests, 1122 and 1211), hand on tool used to remove access panel (underwater tests except 1122 and 1211)--Rigid leg restraint engagement consists of connecting the restraint snap hook to an eye on the mockup. Foot restraint engagement consists of putting feet in restraint and connecting strap tether to mockup. Cage restraint engagement consists of getting into the cage and connecting strap tether to top ring of cage.

4. Fasten Tool Kit

(Start time-hand on restraint; stop time-hand on tool used to remove access panel)--Unfasten tool kit from angle iron rib and position on two angle iron ribs. While holding in position with one hand, use other to obtain clamp and clamp tool kit to rib. Obtain second clamp and use to clamp kit to second angle iron rib. (This task was deleted for all underwater tests except 1122 and 1211.)

TABLE 3-9 (Continued)

5. Remove Four Bolts in Access Panel

(Start time-hand on tool used to remove access panel), (stop time-hand on clamp)--Remove the tool from the took kit, remove the first bolt and put it in the tool kit, remove another bolt and put this bolt in tool kit, remove third bolt, put third bolt in tool kit, remove the fourth bolt, put the fourth bolt in the tool kit, return the tool to the tool kit, and put hand on clamp.

6. Clamp Panel to Spacecraft Mockup

(Start time-hand on clamp; stop time-hand on tool needed for next task)--Remove the clamp, remove the access panel, position the access panel for attachment to the maintenance mockup, clamp the panel to the mockup, and put hand on next tool. (Hand is on valve for difficult tests.)

7. Turn Off Valve on Tubing

(Start time-easy tests, hand off cutters, difficult tests, hand on valve; stop time-easy tests, hand contact with wrench, difficult tests, first contact of wrench to tube connection)--For the easy tests, the tasks included positioning for reach, turning off the valve, and then touching the tool used in the next task. In the difficult maintenance tests, the task included turning the valve off, procuring the two wrenches used in disengaging the tube connection, positioning and making contact with the first wrench on part of the union.

8. Cut Wires to Maintenance Box

(Start time-hand contact with cutters; stop time-easy tests, hand on valve, difficult tests, hand on screwdriver)--For the easy tests, the task included removing the cutters from the tool kit, clipping the first wire, clipping the second wire, returning the cutters to the tool kit, and touching the valve. For the difficult tests, all the above was done except the subject grasped the screwdriver hanging from his wrist instead of touching the valve.

9. Disengage Tube-One Wrench

(Start time-hand contact with wrench, stop time-hand off wrench)--Remove wrench from tool kit, disengage fitting holding tube to top of maintenance box, and return wrench to tool kit.

10. Disengage Tube-Two Wrench

(Start time-first contact of wrench to connector; stop time-hand touches hammer in tool kit)--Use two wrenches to disengage union of tubing leading to the top of the black box, return first wrench to tool kit, return second wrench to tool kit, and put hand on hammer.

11. Remove Two Bolts to Maintenance Box

(Start time-easy tests, hand off wrench, hard tests, hand on tool; stop time-easy tests, hand off tool, hard tests, hand on lanyard)--For the easy tests, the task included removing the tool used to remove the two bolts, removing the first bolt and placing it in the tool kit, removing the second bolt and placing it in the tool kit, replacing the tool in the kit. For the hard tests, the task included removing the tool from the kit removing the first bolt and placing it in the tool kit, removing the second bolt and placing it in the tool kit, replacing the tool in the kit, and touching the lanyard in the tool kit.

12. Remove Maintenance Box and Secure to Spacecraft Mockup

(Start time-hand off wrench; stop time-first movement of subject to access panel)--Remove the lanyard from the tool kit, attach the maintenance box to the lanyard, and attach the lanyard to the spacecraft mockup.

13. Position Access Panel in Opening

(Start time-first movement of subject toward panel; stop time-position of first fastener in panel for finger tightening)--Hold access panel with one hand and release clamp with other, position access panel in opening, procure first fastener from tool kit and finger tighten, and touch tool for tightening bolts.

14. Finger Tighten Bolts in Access Panel

(Start time-positioning of first fastener on panel for finger tightening; stop time-hand on tool in kit)--Finger tighten first bolt, procure second bolt from kit and finger tighten, procure third bolt from kit and finger tighten, procure fourth bolt from kit and finger tighten, and touch tool for tightening bolts.

15. Tighten Bolts in Access Panel With Wrench

(Never tightened all four bolts).

16. Attach Lanyard to Maintenance Box

(Start time-hand on lanyard; stop time-first movement of S to panel)--Remove maintenance box from access opening, attach lanyard to maintenance box, and attach lanyard to spacecraft mockup.

17. Release Maintenance Box end Release Restraint

(Start time-easy tests, tool contact with kit, hard tests, hand on lanyard; stop time, visual separation of restraint)--Easy tests, remove maintenance box from spacecraft mockup, attach to suit shell, and disengage restraint. For hard tests, remove maintenance box from access opening and remove lanyard, attach lanyard to maintenance box and to suit shell and release restraint.

18. Traverse to Hatch With Maintenance Box

(Start time-visual separation of restraint; stop time-last body segment to clear hatch)--This task required the subject to use his hands and a locomotion aid to move from his work station to the hatch.

19. Punch Rivet on Top of Maintenance Box

(Start time-hand touches hammer in tool kit; stop time-hand on next tool)--Remove hammer from tool kit, remove punch from tool kit, place punch on rivet and strike it with the hammer until the rivet has been adequately center-punched, return the hammer to the tool kit, return the punch to the tool kit, and place hand on the tool to be used in the next task.

20. Drill Out Rivet

(Start time-hand on drill or brace; stop time-hand on hammer)--Remove drill or brace from tool kit, drill until the rivet has been removed, replace drill or brace in tool kit, and put hand on next tool.

21. Remove Top From Maintenance Box and Fasten to Spacecraft Mockup

(Start time-hand on screwdriver; stop time-hand on tool for next task)--Remove screwdriver from tool kit, loosen first screw securing top, loosen second screw securing top, put wrist lanyard attached to screwdriver around wrist, remove clamp from tool kit, remove top from maintenance box, clamp top to spacecraft mockup, put hand on tool for next task.

22. Remove Switch From Maintenance Box

(Start time-hand on screwdriver; stop time-release of second switch from tool kit)--Remove first screw from switch, remove second screw from switch, remove switch from maintenance box, place switch in tool kit, and remove replacement switch from kit.

23. Replace Switch in Maintenance Box

(Start time-release of second switch from tool kit; stop time-hand touching tool needed in next task)--Place switch in maintenance box, tighten first screw, and touch tool used in next task.

24. Strip Insulation From Wires

(Start time-hand touching wire strippers; stop time-hand touching pliers)--Remove wire strippers from tool kit, strip first end of wire, strip one inch from end of second wire, return wire strippers to tool kit, and put hand on pliers.

25. Loop Two Wires and Place Under Screws

(Start time-hand on pliers; stop time-hand free of pliers)--Remove pliers from tool kit, loop stripped end of first wire and place under screw, loop stripped end of second wire and place under screw, and return pliers to tool kit.

26. Tighten Two Wires Under Screws

(Start time-hand free of pliers; stop time-hand free of screwdriver)--Grasp screwdriver hanging on lanyard from wrist, tighten first screw, tighten second screw, and release screwdriver.

TABLE 3-9 (Continued)

27. Disengage Pipe

(Start time-hand on pipe wrench; stop time-first wrench to touch tool kit)--Remove first pipe wrench, remove second pipe wrench, using two wrenches loosen first union, using two wrenches loosen second union, and touch tool kit with first pipe wrench.

28. Put Pipe in Kit

(Start time-first wrench to touch tool kit, stop time-pipe segment contained in kit)--Put first pipe wrench in kit, put second pipe wrench in kit, loosen first union with hands, loosen second unions with hands, remove segment, and place segment under bungee cords on tool kit.

29. Move Two Wires From Under Screws to Nuts and Tighten

(Start time-pipe segment contained in kit; stop time-hand on file)--Remove wrench from tool kit, remove screwdriver from tool kit, remove first wire on terminal board with screwdriver and place on bypass connector, remove second wire from terminal board with screwdriver and place on bypass connector, tighten first wire under nut on bypass connector with wrench, tighten second nut on bypass connector with srench, return wrench to tool kit, return screwdriver to tool kit, and place hand on file.

30. File Notch

(Start time-hand on file; stop time-hand on tool for next task)--Remove file from tool kit, file notch on bar to maintenance box large enough for saw blade to be retained, return file to tool kit, and touch tool needed for next task.

31. Saw Bar

(Start time-hand on saw; stop time-hand on tool for next task)--Remove saw from tool kit, saw bar until completely severed, return saw to tool kit, and place hand on tool to be used in next task.

32. Cut Bolt

(Start time-hand on bolt cutters; stop time-hand on tool for next task)--Remove bolt cutters from tool kit, cut rod leading to maintenance box, return bolt cutters to tool kit, and place hand on tool to be used in next task.

TABLE 3-10

PROCEDURES FOR ANTENNA ASSEMBLY
TASK SEQUENCE

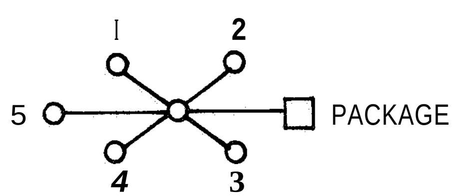
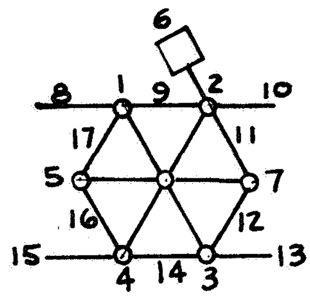
STEP	DESCRIPTION
1.	Subject moves via rigid pole to hatch and attaches line one.
2.	Procures first package and attaches line two to the package.
3.	Attaches snap on package over line one.
4.	Subject plays out both lines and moves via hand rail to antenna boom to work position one.
5.	Subject engages restraint.
6.	Attaches line one to maintenance boom restraint support, pulls line taut and ties off.
7.	With line two, subject pulls package along line one to the work station.
8.	Procures package and engages in joint on front of antenna boom.
9.	Subject removes first joint/beam from package and engages.
10.	Repeats joint/beam engagement for five joints as follows: 
11.	Subject removes package and engages on top of joint 2.
12.	Removes sixth joint/beam and places it where package was originally attached.
13.	Subject removes beam and engages in joint one to left.
14.	Beam two is removed and placed in joint number two to right.

TABLE 5-10 (Continued)

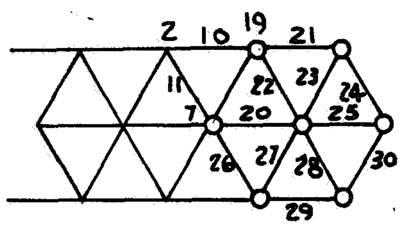
STEP	DESCRIPTION
15.	Subject continues to build antenna to the following configuration.



STEP	DESCRIPTION
16.	Subject coils line two and attaches to self.
17.	Releases line one at antenna work station.
18.	Moves via antenna boom to maintenance boom connection at mockup.
19.	Procures tool from holder and releases locking bolt on maintenance boom.
20.	Moves boom to work position two (marked on plate).
21.	With tool tightens maintenance boom lock nut in position. (At this time, divers remove leg restraint hardware from maintenance boom and replace with the foot restraint hardware.)
22.	Subject releases safety line and moves via antenna boom and hand rail to hatch.
23.	Attaches safety line.
24.	Procures second package and snaps to line one.
25.	Attaches line two to package and plays lines and package out.
26.	Attaches both lines to self.
27.	Moves via rigid rope and hand holds to work station two.

TABLE 3-10 (Continued)

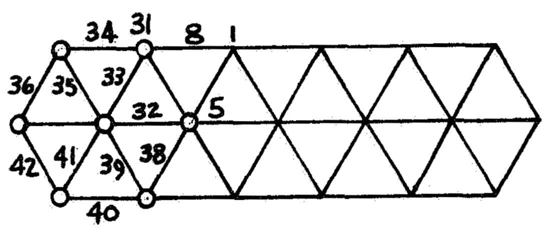
STEP	DESCRIPTION
28.	Subject attaches safety line and engages restraint.
29.	Pulls line one taut.
30.	Attaches to foot restraint hardware and ties off.
31.	Pulls line two and retrieves package.
32.	Engages package at antenna joint 7.
33.	Procures joint/beam and attaches to beam 10.
34.	Removes package and repositions at joint 19.
35.	Subject repeats joint and beam engagements for antenna as follows:



STEP	DESCRIPTION
36.	Subject coils line two and attaches to self.
37.	Releases line one at work station.
38.	Moves via hand holds and rigid rope to maintenance boom connection at mockup.
39.	Fastens safety line.
40.	Procures tool from holder and releases locking bolt on maintenance boom.
41.	Subject moves boom to work position three (marked on plate).
42.	With tool, tightens boom locking bolt. (At this time, divers remove foot restraint hardware from maintenance boom and replace it with cage restraint hardware.)

TABLE 3-10 (Continued)

STEP	DESCRIPTION
43.	Subject releases safety line and moves via hand rail to hatch.
44.	Subject attaches safety line.
45.	Procures third package and snaps package to line one.
46.	Attaches line two to package and plays line and package out.
47.	Attached both lines to self.
48.	Moves via rigid pole to work station three
49.	Attaches safety line and gets in restraint.
50.	Pulls line one taut.
51.	Attaches to top rail of cage and ties off.
52.	Pulls line one and retrieves package.
53.	Engages package at antenna joint 5.
54.	Procures joint/beam and attaches to beam 8.
55.	Removes package and repositions at joint 31.
56.	Subject repeats joint and beam engagement for the antenna as follows:



STEP	DESCRIPTION
57.	Subject coils line two and attaches to self.
58.	Releases line one at work station.
59.	Releases safety line and disengages from restraint.
60.	Moves via rigid pole to hatch.

packages was attached to the face of the antenna dish while the other was being unfolded and attached. After attaching the first two packages, the subject repositioned the boom and procured the next two panel packages, attached them to the antenna face, repositioned the boom, procured the last two panel packages, and attached them to the antenna face. At each repositioning of the boom, the restraint mode was changed by the diver. The general procedures for assembly of the antenna face are listed in Table 3-11.

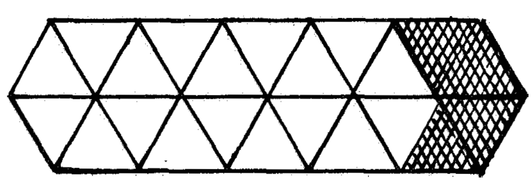
The subject received instructions for assembling the large rigid modules during the test. The first task accomplished by the subject was that of positioning the boom. The subject then bolted section to section to complete assembly. After completion of the assembly of the two modules, the bottom module was attached to the top module with bungee cords. The subject pulled both module assemblies to his work position. He used a bungee cord to tether the module to his work station. Mating of the two modules was accomplished by rotating the modules while drawing them closer together and securing the bolts. The subject then traversed to the opposite side of the module and attached a rope line. He then traversed to the side of the tank and attached the other end of the rope line. He returned to his work station and untethered the module. He traversed back to the ladder and tethered himself. He then used the rope line to pull the module to the ladder and tied the module to the ladder.

As in the large rigid module assembly, the subject received instructions for the erection of the large inflatable modules during the test. The subject procured the first folded inflatable module at the spacecraft mockup hatch, traversed to the end of the boom, unfolded the module, and placed the module on the boom near the space craft mockup in such a manner that the boom was through the center hole of the doughnut shaped inflatable module. The subject returned to the hatch, procured the second inflatable module, and placed it over the boom in the same manner as the first. The second module was positioned approximately 10 ft farther from the spacecraft mockup than the first module. The subject then procured one of the solid extension poles, fastened it in place between the two modules, and extended the pole to full length. Next, the other three extension support poles were positioned and extended. The subject attached the fill hose to the module nearest the maintenance mockup and opened the valve. When this module was completly inflated with water the subject closed the valve, detached the fill hose, attached it to the second module, and opened the fill valve. Upon inflation of the second module, the subject detached the fill hose, attached a rope line at one point on the module, traversed to the ladder at the west side of the tank, and pulled the module to the ladder.

TABLE 3-11

PROCEDURES FOR ANTENNA PANEL TEST
TASK SEQUENCE

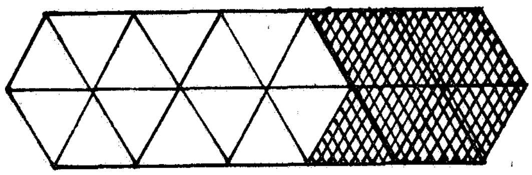
STEP	DESCRIPTION
1.	Subject moves via rigid pole to hatch and attaches line one.
2.	Procures two packages and attaches line two to the packages.
3.	Attaches snaps on packages over line one.
4.	Subject plays out both lines and moves via hand rail to antenna boom to work position one.
5.	Subject engages restraint.
6.	Attaches line one to maintenance boom restraint support, pulls line taut and ties off.
7.	With line two, subject pulls packages along line one to the work station.
8.	Procures packages and attaches to antenna dish.
9.	Removes first package from stowed position and positions package for attachment.
10.	Subject makes first connection at the top of the antenna and moving clockwise attaches each exterior connection of the first panel.
11.	Subject moving clockwise attaches the two connections on the next panel and continues this procedure for the next two panels.



12.	Subject removes stowed package and positions for attachment.

TABLE 3-II (Continued)

STEP	DESCRIPTION
13.	Proceeding as with the first package, subject attaches and connects package two to the antenna.



STEP	DESCRIPTION
14.	Subject coils line two and attaches to self.
15.	Releases line one at antenna work station.
16.	Releases restraint.
17.	Moves via antenna boom to maintenance boom connection at mockup.
18.	Fastens safety line.
19.	Procures tool from holder and releases locking bolt on maintenance boom.
20.	Moves boom to work position two (marked on plate).
21.	With tool tightens maintenance boom lock nut in position. (At this time, divers remove leg restraint hardware from maintenance boom and replace with foot restraint hardware.)
22.	Subject releases safety line and moves via antenna boom and hand rail to hatch.
23.	Attaches safety line.
24.	Procures package 3 and 4 and snaps to line one.
25.	Attaches packages 3 and 4 to line two and plays lines and package out.

TABLE 3-11 (Continued)

STEP	DESCRIPTION
26.	Attaches both lines to self.
27.	Releases safety line and moves via rigid rope and hand holds to work station two.
28.	Engage restraint and attach safety line.
29.	Pulls line one taut and ties off on restraint hardware.
30.	Pulls line two and retrieves package.
31.	Procures packages and attaches to antenna dish.
32.	Removes first package (No. 3) from stowed position and positions package for attachment.
33.	Subject makes first connection at the top of the antenna and moving clockwise, attaches each exterior connection of the first panel.
34.	Subject moving clockwise attaches the two connections on the next panel and continues this procedure for the next two panels.
35.	Subject moving clockwise attaches the two connections on the next panel and continues this procedure for the next two panels.
36.	Subject removes stowed package (No. 4) and positions for attachment.
37.	Proceeding as with package (No. 3), subject attaches and connects package two to the antenna.
38.	Subject coils line two and attaches to self.
39.	Releases line one at antenna work station two.
40.	Releases restraint and safety line.
41.	Moves via hand holds and rigid rope to maintenance boom connection at mockup.

TABLE 3-II (Continued)

STEP	DESCRIPTION
42.	Fastens safety line.
43.	Procures tool from holder and releases locking bolt on maintenance boom.
44.	Subject moves maintenance boom to work position three (marked on plate).
45.	With tool, subject tightens locking bolt. (At this time, divers remove foot restraint hardware from maintenance boom and replace it with cage restraint hardware.)
46.	Subject releases safety line and moves via hand rail to hatch.
47.	Subject attaches safety line.
48.	Procures packages 5 and 6 and snaps to line one
49.	Attaches line two to packages 5 and 6 and plays lines, and packages out.
50.	Attaches both lines to self.
51.	Moves via rigid pole to work station three.
52.	Attaches safety line and gets in restraint.
53.	Pulls line one taut and ties off on restraint hardware.
54.	Pulls line two and retrieves package.
55.	Procures packages and attaches to antenna dish.
56.	Removes first package (No. 5) from stowed position and positions package for attachment.
57.	Subject makes first connection at the top of the antenna and moving clockwise attaches each exterior connection of the first panel.
58.	Subject moving clockwise attaches the two connections on the next panel and continues this procedure for the next two panels.

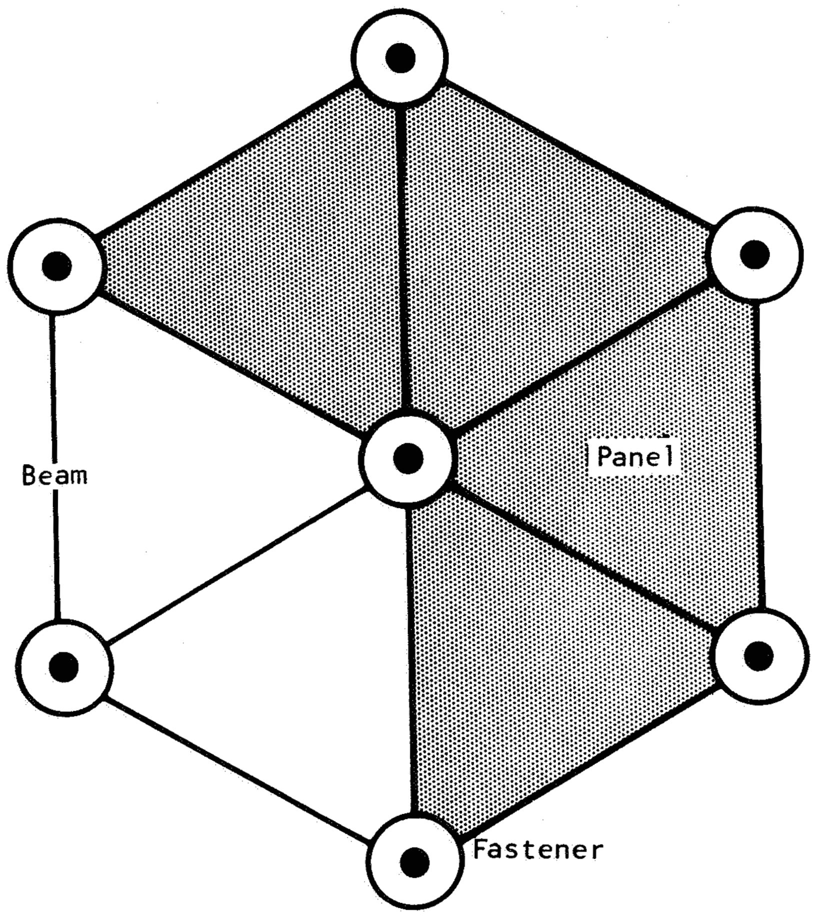
TABLE 3-II (Continued)

STEP	DESCRIPTION
59.	Subject removes stowed package (No. 6) and attaches and connects the last two panels.
60.	Subject coils line two and attaches to self.
61.	Releases line one at work station.
62.	Releases safety line and disengages from restraint.
63.	Moves via rigid pole to hatch.

The last large module test conducted was one in which the subject assembled a section of the antenna in the six-degree-of-freedom suspension simulator. Again, the subject was allowed the freedom of assembling the antenna in the manner he desired. The hardware used in the assembly was handed to him piecemeal by an assistant throughout the assembly process. The final configuration that was assembled by the subject in the suspension simulator is schematically depicted in Figure 3-1.

The different sizes of tools and bolts used throughout testing and the categories to which they were assigned are listed in Tables 2-1 and 2-2.

The tool and fastener variables used in each test are listed by task in Table 3-12. Those tasks that-did not require the use of a tool or fastener, such as traversing or engaging restraints, are not included in this table. The tasks performed under full gravity, unsuited conditions are not included either, since these tests were training events to furnish the subject with some experience in performing the task procedures, to give the human engineer practice in recording observations and measuring task times, to provide evidence that the tasks could at least be performed by the subject in an unsuited condition, and to evaluate different hardware concepts.



Shaded Area
Represents
Panel
Attachment

Figure 3-1. Schematic of Antenna Section Assembled in Suspension Simulator

TABLE 3-12

TOOL AND FASTENERS USED IN TASKS

TASK DESCRIPTION	SIMULATION, TASK, LOCOMOTION AID, RESTRAINT CODE	TOOL AND/OR FASTENER MANIPULATED
FASTEN TOOL KIT	2101	2 Vise Grips
	2102	2 "C" Clamps
	2201	2 Spring Clamps with Bolt Separator
	2202	2 Vise Grips
	2301	2 "C" Clamps
	2302	2 "C" Clamps
REMOVE BOLTS TO ACCESS PANEL	1111	Ratchet with 3/4 in. Socket, Large Hex-Head Bolts
	1133	Ratchet with 9/16 in. Socket, Medium Hex-Head Bolt
	1144	"T" Handle with 3/16 in. Int. Wrench Head, Small Int. Bolts
	1155	15/32 in. Tip Width Screwdriver, Large Slotted Bolts
	1244	15/32 in. Tip Width Screwdriver, Medium Slotted Bolts
	1255	"T" Handle with 3/16 in. Int. Wrench Head, Small Int. Bolts
	1311	6/32 in. Tip Width Screwdriver, Small Slotted Bolts
	1322	15/32 in. Tip Width Screwdriver, Large Slotted Bolts
	1344	6/32 in. Tip Width Screwdriver, Bolt Size
	1355	15/32 in. Tip Width Screwdriver, Small Slotted Bolts
	1336	15/32 in. Tip Width Screwdriver, Medium Slotted Bolts
	2101	Ratchet with 3/4 in. Socket, targe Hex-Head Bolts (20# Torque)
	2102	"T" Handle with 3/8 in. Int. Wrench Head, Large Int. Bolts (20# Torque)
	2201	9/16 in. Closed End Wrench, Medium Hex. Head Bolts (20# Torque)
	2202	"T" Handle with 3/16 in. Int. Wrench Head, Small Int. Bolts (20# Torque)
	2301	"T" Handle with 3/16 in. Int. Wrench Head, Small Int. Bolts

TABLE 3-12 (Continued)

TASK DESCRIPTION	SIMULATION TASK, LOCOMOTION AID, RESTRAINT CODE	TOOL AND/OR FASTENER MANIPULATED
REMOVE BOLTS TO ACCESS PANEL (Cont.)	2302 3. 1. 0. 6 3. 2. 0. 6 3. 3. 0. 6	6/22 in. Tip Width Screwdriver, Large Slotted Bolts Ratchet with 3/4 in. Socket, Large Hex Head bolts
REMOVE AND CLAMP ACCESS PANEL	1111 1133 1144 1155 1244 1255 1311 1322 1344 1355 1336 2101 2102 2201 2202 2301 2302	Spring Clamp with Bolt Rope Lanyard Spring Clamp with Bolt String Lanyard "C" Clamp Rope Lanyard Spring Clamp with Rubber Tips Bungee Cord String Lanyard Rope/Stick Lanyard Rope/Stick Lanyard Spring Clamp with Bolt Separator Vise Grips Two Spring Clamps-Rubber Tips "C" Clamp Two Spring Clamps-Rubber Tips Two Spring Clamps-Rubber Tips
CUT WIRES TO MAINTENANCE BOX	1111 1133 1144 1155 1244 1255 2101 2102 2201 2202 3. 1. 0. 6 3. 2. 0. 6 3. 3. 0. 6	Diagonal Cutting Pliers Diagonal Cutting Pliers Diagonal Cutting Pliers Diagonal Cutting Pliers Diagonal Cutting Pliers Diagonal Cutting Pliers Diagonal Cutting Pliers Diagonal Cutting Pliers Combination Pliers Diagonal Cutting Pliers Diagonal Cutting Pliers

TABLE 3-12 (Continued)

TASK DESCRIPTION	SIMULATION, TASK, LOCOMOTION AID, RESTRAINT CODE	TOOL AND/OR FASTENER MANIPULATED
DISENGAGE TUBE CONNECTION TO MAINTENANCE BOX	1111	1/2 in. Open End Wrench
	1133	Self-Adjusting Hook Wrench
	1144	1/2 in. Open End Wrench
	1155	Crescent Wrench
	1244	Crescent and Self-Adjusting Hook Wrench
	1255	9/16 in. and 11/16 in. Open End Wrenches
	2101	1/2 in. Open End Wrench
	2102	Crescent Wrench
	2201	9/16 and 11/16 in. Open End Wrenches
	2202	Crescent and Self-Adjusting Hook Wrench
	3.1.0.6 - 3.2.0.6 3.3.0.6	9/16 in. and 11/16 in. Open End Wrenches
REMOVE BOLTS TO MAINTENANCE BOX	1111	"T" Handle with 3/4 in. Socket, Large Hex Head Bolts
	1133	"T" Handle with 9/16 in. Socket, Medium Hex Head Bolts
	1144	Ratchet with 3/16 in. Int. Wrench Head, Small Int. Bolts
	1155	15/32 in. Tip Width Screwdriver, Large Slotted Bolts
	1311	Crescent Wrench, Small Hex Head Bolts
	1322	15/32 in. Tip Width Screwdriver, Small Slotted Bolts
	1344	"T" Handle with 3/16 in. Int. Wrench Head, Small Int. Bolts
	1355	15/32 in. Tip Width Screwdriver, Small Slotted Bolts
	1336	15/32 in. Tip Width Screwdriver, Small Slotted Bolts
	2101	"T" Handle with 314 in. Socket, Large Hex Head Bolts
	2102	Ratchet with 3/8 in. Int. Wrench Head, Large Int. Bolts
	2301	"T" Handle with 7/16 in. Allen Head, Small Allen Bolts
	2302	15/32 in. Tip Width Screwdriver

TABLE 3-12 (Continued)

TASK DESCRIPTION	SIMULATION, TASK, LOCOMOTION AID, RESTRAINT CODE	TOOL AND/OR FASTENER MANIPULATED
REMOVE MAINTENANCE BOX AND SECURE TO SPACECRAFT MOCKUP	1111	Stick Lanyard
	1133	Stick Lanyard
	1144	Stick Lanyard
	1155	Stick Lanyard
	2101	Snap Lanyard
	2102	Snap Lanyard
POSITION ACCESS PANEL IN OPENING	1111	Spring Clamp with Bolt
	1133	Rope Lanyard
	1144	Spring Clamp with Bolt
	1155	String Lanyard
	2101	Snap Lanyard
	2102	Vise Grips
FINGER TIGHTEN BOLTS IN ACCESS PANEL	1111	Large Hex. Head Bolts
	1133	Medium Hex Head Bolts
	1144	Small Int. Wrenching Bolts
	1155	Large Slotted Bolts
	2101	Large Hex Head Bolts
	2102	Large Int. Wrenching Bolts
TIGHTEN BOLTS IN ACCESS PANEL WITH WRENCH	1111	Ratchet with 3/4 in. Socket, Large Hex Head Bolts
	1133	Ratchet with 9/16 in. Socket, Medium Hex Head Bolts
	1144	"T" Handle with 3/16 in. Int. Wrench Head Small Int. Bolts
	1155	15/32 in. Tip width Screwdriver, Large Slotted Bolts

TABLE 3-12 (Continued)

TASK DESCRIPTION	SIMULATION, TASK, LOCOMOTION AID, RESTRAINT CODE	TOOL AND/OR FASTENER MANIPULATED
TIGHTEN BOLTS IN ACCESS PANEL WITH WRENCH (Continued)	2101 2102	Ratchet with 3/4 in. Socket, Large Hex Head Bolts "T" Handle with 3/8 in. Int. Wrench Head Internal Bolts
ATTACH LANYARD TO MAINTENANCE BOX	1311 1322 1344 1355 1336 2381 2302	Stick Lanyard Stick Lanyard Stick Lanyard Stick Lanyard Stick Lanyard Snap Lanyard Snap Lanyard
RELEASE MAINTENANCE BOX AND RESTRAINT	1111 1133 1144 1155 2101 2102	Stick Lanyard Stick Lanyard Stick Lanyard Stick Lanyard Lanyard with Snaps Lanyard with Snaps
PUNCH RIVET ON TOP OF MAINTENANCE BOX	1244 1255 2201 2202 3.1.0.6 3.2.0.6 3.3.0.6	Center Punch Center Punch Center Punch, 24 oz. Head Hammer Center Punch, 24 oz. Head Hammer Center Punch Hammer
DRILL OUT RIVET	1244 1255 2201 2202 3.1.0.6 3.2.0.6 3.3.0.6	Open Ratchet Bit Brace Hand Drill Hand Drill, Drift Punch, 24 oz. Head Hammer Open Ratchet Bit Brace Hand Drill, Drift Punch, Hammer

TABLE 3-12 (Continued)

TASK DESCRIPTION	SIMULATION, TASK, LOCOMOTION AID, RESTRAINT CODE	TOOL AND/OR FASTENER MANIPULATED
REMOVE TOP FROM MAINTENANCE BOX AND FASTEN TO SPACECRAFT MOCKUP	1244 1255 2201 2202	11/32 in. Tip Width Screwdriver, Vise Grips 11/32 in. Tip Width Screwdriver, "C" Clamp 11/32 in. Tip Width Screwdriver, "C" Clamp 6/32 in. Tip Width Screwdriver, Spring Clamp with Bolt
REMOVE SWITCH FROM MAINTENANCE BOX	1244 1255 2201 3.1.0.6 3.2.0.6 3.3,0.6	11/32 in. Tip Width Screwdriver, 11/32 in. Tip Width Screwdriver 11/32 in. Tip Width Screwdriver "C" Clamp Screwdriver (6/32 in. Tip Width)
REPLACE SWITCH IN MAINTENANCE MAINTENAN BOX	1244 1255 2202 3.1.0.6 3 2.0.6 3,3,0.6	15/32 in Tip Width Screwdriver 11/32 in. Tip Width Screwdriver 11/32 in. Tip Width Screwdriver 6/32 in. Tip Width Screwdriver Screwdriver (6/32 in. Tip Width)
STRIP INSULATION FROM WIRES	1244 1255 2201 2202 3.1.0.6 3 2.0.6 3.3.0.6	Wire Strippers Wire Strippers Wire Strippers Wire Strippers Wire Strippers
LOOP Two WIRES AND PLACE UNDER SCREWS	1244 1255 2201 2202 3.1.0.6 3.2.0.6 3.3.0.6	Long Nose Pliers Long Nose Pliers Long Nose Pliers Long Nose Pliers Long Nose Pliers
TIGHTEN TWO WIRES UNDER SCREWS	1244 1255 2201	15/32 in. Tip Width Screwdriver 11/32 in. Tip Width Screwdriver 11/32 in. Tip Width Screwdriver

TABLE 3-12 (Continued)

TASK DESCRIPTION	SIMULATION, TASK, LOCOMOTION AID, RESTRAINT CODE	TOOL AND/OR FASTENER MANIPULATED
TIGHTEN TWO WIRES UNDER SCREWS (Continued)	2202 3.1.0.6 3.2.0.6 3.3.0.6	6/32 in. Tip Width Screwdriver Screwdriver (6/32 in Tip Width)
DISENGAGE PIPE	1311 1322 1344 1355 1336 2301 2302 3.1.0.6 3.2.0.6 3.3.0.6	(2) 10 in. Pipe Wrenches (2) 10 in. Pipe Wrenches (2) 10 in. Pipe Wrenches (2) 10 in. Pipe Wrenches (2) 10 in. Pipe Wrenches (2) 10 in. Pipe Wrenches (2) 10 in. Pipe Wrenches (2) 10 in. Pipe Wrenches
MOVE TWO WIRES FROM UNDER SCREWS TO NUTS AND TIGHTEN	1311	6/32 in. Tip Width Screwdriver, 11/32 in. Closed End Wrench
	1322	6/32 in. Tip Width Screwdriver, 11/32 in. Closed End Wrench
	1344	6/32 in. Tip Width Screwdriver, 11/32 in. Closed End Wrench.
	1355	15/32 in. Tip Width Screwdriver, 11/32 in. Closed End Wrench
	1336	6/32 in. Tip Width Screwdriver, 11/32 in. Closed End Wrench
	2301	15/32 in. Tip Width Screwdriver, 11/32 in. Closed End Wrench
	2302	15/32 in. Tip Width Screwdriver, 11/32 in. Closed End Wrench
	3.1.0.6 3.2.0.6 3.3.0.6	6/32 in. Tip Width Screwdriver, 11/32 in. Closed End Wrench

TABLE 3-12 (Continued)

TASK DESCRIPTION	SIMULATION, TASK, LOCOMOTION AID, RESTRAINT CODE	TOOL AND/OR FASTENER MANIPULATED
FILE NOTCH	1311	Halfround Metal File
	1322	" " "
	1344	" " "
	1355	" " "
	1336	" " "
	2301	" " "
	2302	" " "
	3.1.0.6	" " "
	3.2.0.6	
	3.3.0.6	
SAW BAR	1311	Hacksaw
	1322	"
	1344	"
	1355	"
	1336	"
	2301	"
	2302	Key Hole Saw
	3.1.0.6	Hack Saw
	3.2.0.6	
	3.3.0.6	
CUT BOLT	1311	Clipper Cut Bolt Clippers
	1322	" " " "
	1344	" " " "
	1355	" " " "
	1336	" " " "
	2301	" " " "
	2302	" " " "
	3.1.0.6	" " " "
	3.2.0.6	
	3.3.0.6	
TIGHTEN BEAM LOCK SCREW	ANTENNA TESTS	3/16 in. Thumb Screw
TIGHTEN CAPTIVE BOLT	LARGE RIGID MODULES	Ratchet with 7/16 in. Socket, 7/16 in. Open End Wrench, 1/4 in. Hex Head Bolts (Captive in hardware)

SECTION 4

GENERAL TEST PROCEDURES

INITIAL NEUTRAL BUOYANCY TESTS

While the test facility was under construction, a series of five neutral buoyancy tests were conducted in a local swimming pool to gain information on the necessary weight configuration to be used in establishing not only neutral buoyancy, but also freedom to move in all planes about the subject's center of gravity. Due to the lack of a properly fitting G-2C suit, the Mark IV pressure suit was used because of its relative anthropometric similarity to the G-2C. The test crew consisted of three men: a subject, a diver, and an observer who also tended the safety line. Upon his arrival at the pool area, the subject was assisted by the observer in donning the Mark IV suit, The diver readied his diving gear and the weight harness to be used in the neutral buoyancy attempt. After completion of suit donning, the diver and observer attached the weight harness and weights to the subject. The safety line was then attached and the suit was pressurized by a set of high-pressure air tanks carried by the subject on his back. The suit pressurization was controlled by the subject. After completion of suit pressurization, the diver assisted the suited man in obtaining different positions in the shallow end of the pool. (If weight configuration changes were apparent, the changes were made at that time.) The diver then led the subject into the deeper end of the pool, at which time various roll, pitch, and yaw motions were attempted. The observer noted any pertinent phenomena, which were later supplemented with information from an interview with the subject. Test length was regulated by the length of the air supply. When the air supply became low, the subject was brought to the shallow end of the pool; the weights were removed by the diver and observer, and the observer assisted the subject in doffing the suit.

FULL GRAVITY MAINTENANCE TESTS--NO PRESSURE SUIT

Before the start of each test, tools and other hardware specified in the test design were collected and organized. This entailed selecting tools to be used in the test sequence and placing them in the appropriate tool kit, making any necessary restraint modifications on the shell, and making all required hardware changes on the spacecraft mockup. The subject was then given a final review of the task sequences, donned the hard shell, and was positioned by the hatch with tool kit in hand.

At the signal of the human engineer, the test was begun and the subject set out to complete his first task, Times of the tasks were kept by the human engineer, as well as recorded observations of positive and negative aspects of equipment and performance. During some of these tests, two human engineer observers were used to take times on the maintenance tasks. Other than this exception, the crew consisted of three men: a subject, a human engineer, and a technician.

FULL GRAVITY MAINTENANCE TESTS--PRESSURE-SUITED SUBJECT

Pretest operations for the full gravity maintenance tests using a pressure-suited subject were the same as those described above with the addition of the subject's donning the G-2C suit and the calibration of the mass spectrometer used for measuring gas partial pressures in the suit. Test procedures were the same as those followed in the unpressurized suit series with the exception of intermittent gas samplings.

The suited full gravity tests required a seven man crew: two human engineer observers, a test subject, a test conductor, an instrumentation technician, a setup technician or general assistant, and a photographer. The two human engineer observers took times on the durations of each task and recorded observations on performance level and hardware usage. The subject was interviewed after the completion of each test and subjective comments were noted. The test subject's assignments included doffing and donning the suit, and learning and performing the task sequences in the proper order. In general, the assistant was required to help the subject doff and don the suit, make the necessary restraint changes on the shell, make the necessary changes on the maintenance mockup, assemble the required tools and place them in the tool kit, and perform or assist the subject in any task element the subject could not perform.

The test conductor monitored the suit pressure and flowmeter instrumentation and was required to maintain prescribed suit pressure and flow. He kept in constant communication with the instrumentation technician for information on oxygen and carbon dioxide partial pressures in the suit. He also kept in constant communication with the subject, inquiring about his physical state and degree of fatigue. The instrumentation technician was responsible for periodic calibrations and for constant monitoring of the mass spectrometer. He also monitored the suit outlet temperatures and relayed his information to the test conductor. The photographer took 16 mm movies of the task sequences, getting closeup views of any tasks creating difficulty or requiring great dexterity or force.

WATER SUBMERSION TESTS--SIMULATED WEIGHTLESSNESS BY NEUTRAL BUOYANCY

Test Personnel and Assignments

The test crew for the underwater tests consisted of seven men: two divers, a human engineer observer, a test conductor, a test subject, an instrumentation technician, and a safety line attendant. The two divers were responsible for watching and assisting the subject during his entire time underwater. They made all underwater equipment changes. They assisted the subject in ascending and descending and made any necessary weight configuration changes. They made all attachments and detachments of equipment to the subject while he was on the platform. They were responsible for maintaining all the diving gear and the test hardware in the tank. The test subject was responsible for carrying out the task sequences to the best of his ability. He was instructed not to take advantage of the drag forces of the water. The subject was also responsible for maintaining the G-2C pressure suit. (This included all necessary lubrication and sterilization following each test day.) The photographer was responsible for filming the tests and developing and supplying copies of all film taken. The instrumentation technician was responsible for calibrating the mass spectrometer before each test and checking this calibration periodically during each test. His duties also entailed keeping the intercommunications system operable and maintaining all instrumentation used for testing. The safety line attendant assisted the subject in and out of the tank, checked all connections to the suit, and tended the safety line at all times while the test subject was submerged. The test conductor operated the suit ECS system and kept in constant communication with the subject and other test personnel. He was responsible for supervising each test and coordinating all test personnel. The human engineer observed all task sequences and recorded times on maintenance task durations. He was responsible for initiating all tests, observing all task sequences, and noting performance levels. The human engineer was also responsible for recording the subject's comments and for providing task sequence material for the subject to learn and accomplish.

Typical Sequence of Events

Before each test, the mass spectrometer was calibrated and all other instrumentation checked for operability. The divers made the necessary hardware changes and collected the tools needed for performing the task sequences. For all the maintenance tests, the human engineer listed the task sequences on a special underwater writing slate. The slate was attached to the spacecraft mockup in a position that allowed the subject to refer to it at any time during the test. This was done to minimize the number of task deletions due to oversight. The subject was required to learn and remember the procedures for the assembly of the antenna. However, during the erection of the large rigid and inflatable modules, the subject was told what tasks to perform and when to perform them. The subject was assisted in donning the suit and was accompanied from the suit dressing room to the water tank facility. Upon arriving at the lowering platform, the subject was assisted over the edge of the tank and onto the platform by the safety line attendant and the divers. The shell was then attached and the straps tightened, the suit inlet and outlet hoses connected, the communications plug connected, and all connections checked for integrity. The safety line attendant relayed all events occurring on the lowering platform to the test conductor. After the suit communications plug was connected, events were relayed to the test conductor by the subject. The helmet visor was closed and the suit pressurized. The divers led the subject to the ladder at the west side of the tank, and the subject then descended to the bottom of the tank at a rate slow enough to allow the test conductor time to maintain the proper suit pressure and flow conditions.

After reaching the bottom of the tank, the subject directed the divers to make slight changes in the weight configuration until the best possible neutral buoyant condition was obtained. The divers then led the subject to the prescribed starting position, and at a signal from the human engineer the test was started.

During each test, two scuba divers remained underwater with the subject in case of any emergency. They also kept the air supply lines free from binding and assisted the subject when he could not perform a task. The test conductor constantly made minor adjustments with the suit pressure and flow valves, necessitated by the subject's vertical translations while doing work. The human engineer timed all task sequences and noted his observations of work positions and hardware effectiveness. An observer stood on the tank catwalk and tended the safety line. A photographer took films of the tasks performed by the subject. Periodic oxygen and carbon dioxide gas samples were taken on the mass spectrometer.

At the conclusion of each test, the divers led the subject to the ladder and all three ascended at a rate that allowed the test conductor enough time to maintain suitable pressure and flow conditions. Upon arriving at the surface, the subject was brought to the lowering platform and assited in obtaining a standing position. The suit was depressurized, the visor opened, the hoses and intercom disconnected, and the shell removed. The subject was assisted out of the tank and accompanied to the suit dressing room. He was assisted in doffing the suit, and after showering, gave subjective comments in an interview with the human engineer. Those comments that had not been noted during the test were written down.

SIX-DEGREES-OF-FREEDOM SIMULATOR TESTS--SIMULATED WEIGHTLESSNESS

Testing was conducted for several days on the six-degrees-of-freedom simulator. Before each test, the necessary hardware was set up, the required tools assembled, and the mass spectrometer calibrated. Electrocardiogram sensors were attached to the subject and he was then assisted in donning the suit. After suit donning, the subject was led to the test site where the communication plug and suit ECS hoses were connected. The subject was strapped into the simulator and pressurized. After the proper suit flow rate and pressure were obtained, the test was started. During the test, the subject performed the task sequences while the human engineering observers recorded times on task duration rnd took notes of what they observed. Films of the task sequences were taken. At the conclusion of the test, the subject was depressurized and unstrapped from the simulator. The communications plug and suit inlet and outlet hoses were disconnected, and the subject was accompanied to the suit dressing room. He was assisted in doffing the suit. Later, subjective comments were noted in an interview with one of the human engineers. The test crew comprised essentially the same members as those In the suited, full gravity tests. Job assignments were the same with the exception of the Instrumentation technician, who had the additional responsibility of monitoring the subject's electrocardiogram. The services of an experienced, electrocardiogram sensor technician were required to attach the sensors to the subject.

SECTION 5

HUMAN ENGINEERING OBSERVATIONS

INTRODUCTION

The orientation for the human engineering observations during this study was based on the knowledge that a considerable amount of the information available from the tests would not be obtained through the measuring and recording techniques to be used. In addition, a need existed for providing analytical information about the numerous simultaneous interactions of the test variables. Two major sources of information were used to provide these requirements.

The first source of data was direct observation of tests events; films were taken to furnish an unchanging data source that could be re-used for specific analytical purposes. It was assumed that as analysis progressed during the study, certain new insights would be made that would require reexamination of the test film. It was believed that observations should be made of all the test subject's behavior during the test, and that these observations, coupled with the test subject's comments and interviews, would provide insights into some of the problem areas anticipated in a study of this scope.

The second major source of information was the time required to perform the numerous tasks elements of the work situations. A procedure was established to have the human engineering observer follow the subject throughout the test with a check list of the task sequences, taking times for the elements of the sequence and recording them next to a printed description of the work. At this time, the observer could note and record his observation relative to the man/machine interface problems. The observer's secondary objective was to evaluate the effect of the independent variables in each test mode (see Table 3-1).

The subjective aspect of this method is readily acknowledged. It is tempered, however, by the consideration that only the obvious conclusions were drawn from the observations. In the test situation, the interaction at the man-machine interface is extremely complex. The observer can attend to only one element at a time, and his judgment must be relied on to select the most essential and critical aspect for his attention. The discussion that follows is largely representative of this method. The results of the human engineering observations are organized in terms of observations about specific aspects of the independent variables of: (1) restraints, (2) tools, (3) locomotion aids, (4) large module erection and assembly, (5) general observations on EVA work, (6) recommendations, and (7) conclusions.

RESTRAINTS

As the tests progressed during the underwater simulation, the subjects became more adept in performing the maintenance tasks. A portion of this skill improvement must be attributed to learning as a result of repeating some portions of the tasks. However, the body position taken by the subject for work performance was one function observed that was constantly associated with successful task performance. The more stable the worker, the more successful the task completion. The stability of the subject was not necessarily directly related to the restraint used. Some restraints, although restrictive and providing good support to the subject, did not provide the subject the freedom necessary to get a good work position.

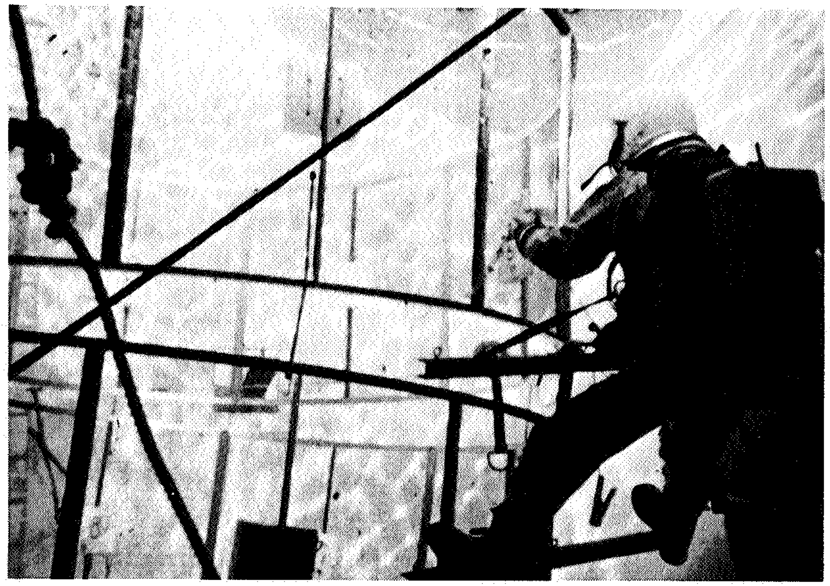
The most prevalent stable work position observed during the tests is referred to as the lineman's position, due to its similarity to the position taken by men working on poles with overhead wires. This position basically consists of the legs pulling the body up and/or out against a restraint mechanism attached at the worker's waist. It was this position, or variations of it, that provided the subjects with the best and most stable work positions during the underwater simulation (Figure 5-1).

The lineman's position could be readily assumed most of the time when the subject was using either the cage or foot restraints. It was more difficult to obtain the lineman's position while using the rigid leg restraints. The subject, however, continually sought this position, or some variation of it, in order to do the work (Figure 5-2). Other positions, although often quite functional and effective, generally were not used by the subject until after he had tried and failed to obtain a lineman's position.

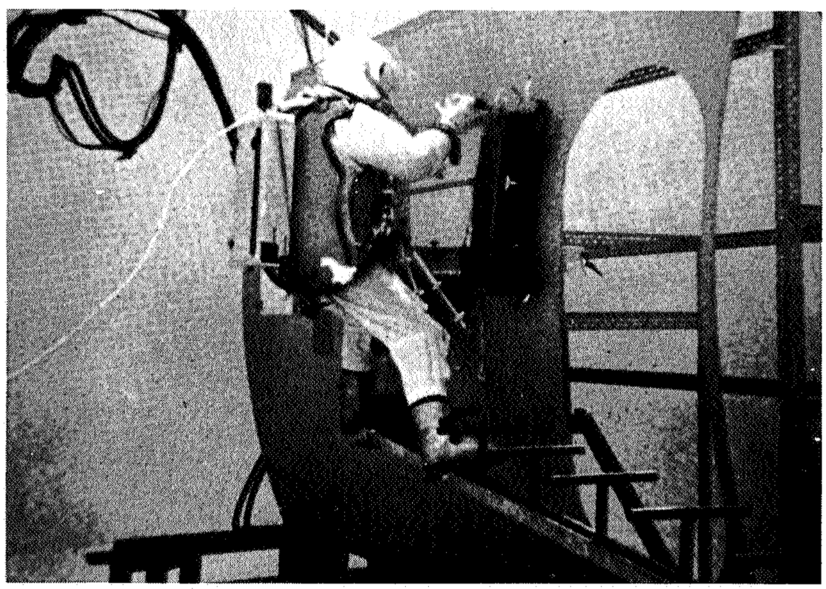
The proper positioning of the subject to the work was essential in all but the most simple and short-time-span tasks. The necessity of proper positioning was required due to the negative aspects associated with the resistance of a pressurized suit, the limitation and hindrance to the field of vision, the limited arm reach capability, and the lack of adequate tactile feedback through the gloves. If the proper positioning was not attained, it was highly probable that the subject could not perform a complicated task.

Rigid Leg Restraints

Failure to obtain the proper optimal position or to maintain the position was the outstanding negative observation of the rigid leg restraints. Several aspects are related to this positioning difficulty. One of these is that the rigid leg restraints tend to hold the worker away from his work (Figure 5-2). Another difficulty is the pivoting of the connecting points, consisting of an eye bolt on the mockup and a snap-hook connector on the restraint arm. The rigid leg restraint was attached to the subject with a lockable universal joint. The locking mechanism was not strong enough to



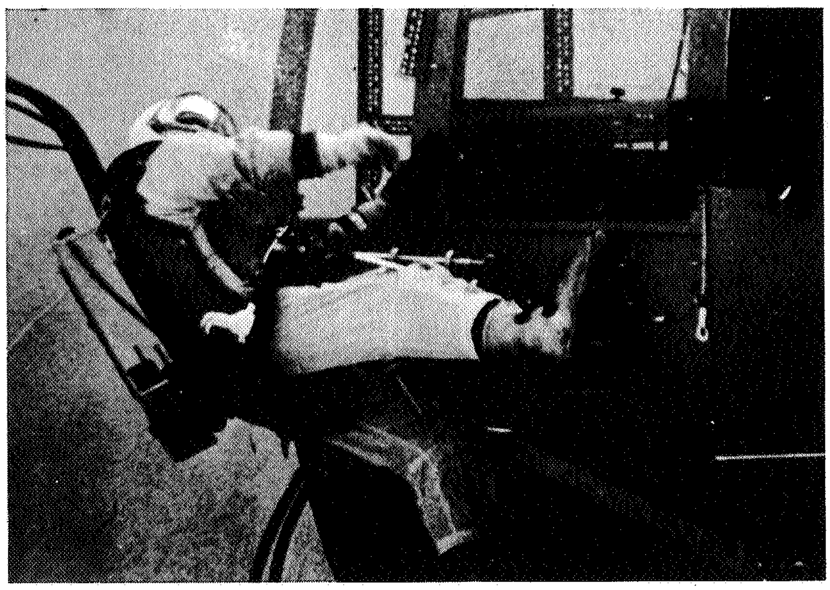
LINEMAN'S POSITION



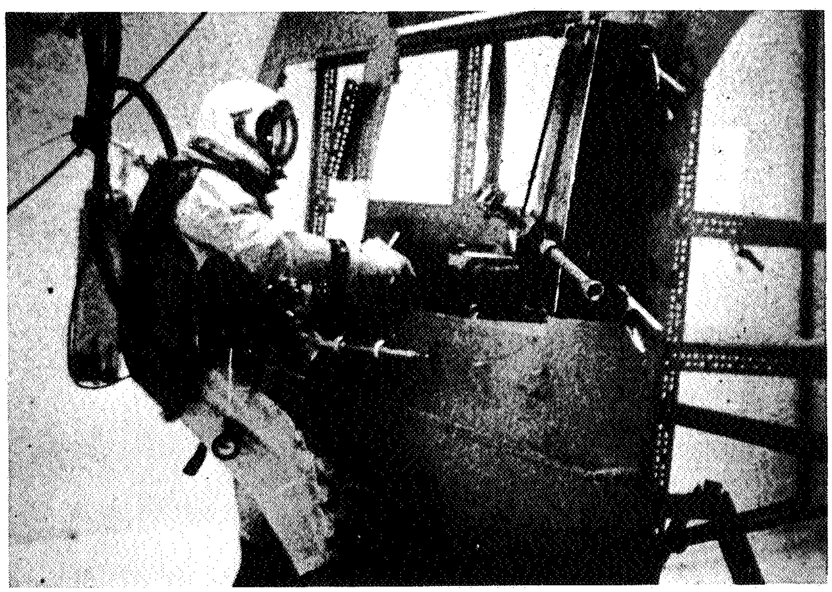
LINEMAN'S POSITION

F-7290

Figure 5-1



VARIATION OF LINEMAN'S POSITION



F-7291

RIGID LEG RESTRAINT

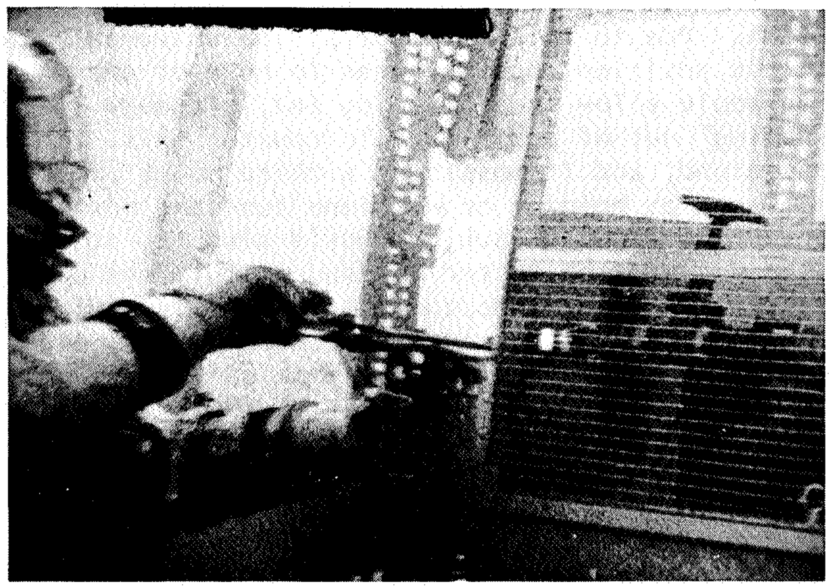
Figure 5-2

prevent movement of the joint from the forces applied to it by the subject's movements during work. Que to this slippage of the universal, the worker could not maintain his position once he began to move or exert force. The eye bolt connection would allow free pivoting and, although still connected, the worker would "swing" out of position. To counter this, the subject attempted to get a second, and if possible, a third point of contact. This was usually accomplished by holding on with one hand and working with the other hand only (Figure 5-3). The subject would also try to hook a leg on or into the mockup. When the latter was successful, the position would become quite stable (Figure 5-3). Most of the time this could not be accomplished, due to the smooth surface of the mockup providing no openings or places in which the subject could bind or hook a foot. Thus, the subject would butt his toe or toes against the surface of the mockup and work until the forces from his movements became great enough to overcome the pressure being exerted by his feet, and he would lose his position (Figure *5-4).*

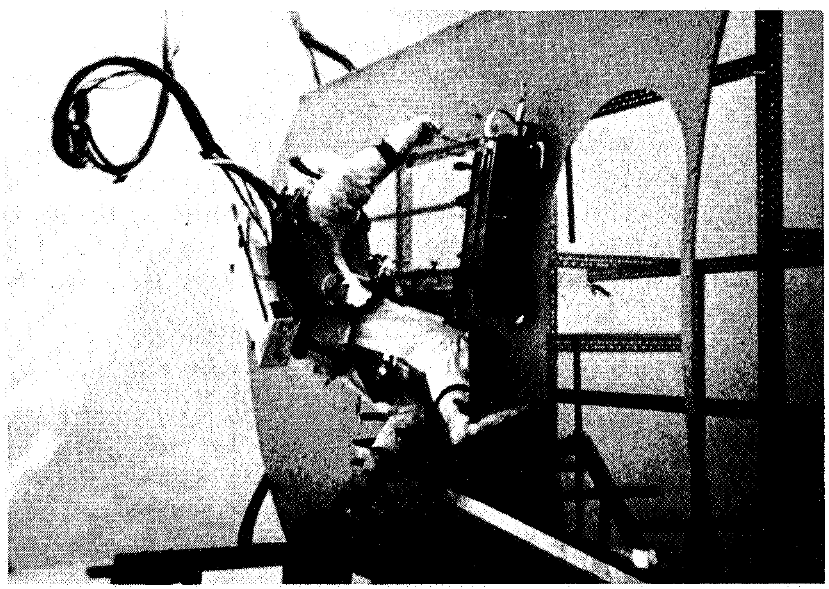
After the subject had removed the access panel and was able to attach one restraint within the access opening, his performance level would improve as a result of the greater stability of his position. By using either his back muscles or his arm, the subject could wedge his head under the top edge of the access opening and become stable. In this position, work could be performed reasonably well (Figure *5-5).* In this position, the leg restraint was more apt to hinder the worker by bending or holding him out and/or away from the position that he wanted to assume.

The use of the rigid leg restraints required a considerable amount of manipulation by connecting and reconnecting when changing positions. It was in this respect that the greatest difference was noted between the one-, two-, and three-leg configuration, the latter being very time consuming. The two- and three-leg restraint configurations both provided a more stable position from which to work than did the single-leg configuration (Figure *5-6).* The single-leg restraint, however, was advantageous in that it allowed greater freedom for the worker to turn from one side to the other (Figure *5-6).* By utilizing the side work position, the subject could get closer to his work and perform one-handed tasks without binding his arm against the interior part of the pressure suit.

From a work performance consideration, the rigid leg restraints were the most unsatisfactory restraints tested. However, many contingencies must be considered before a final judgment is made as to their desirability for EVA tasks, The first is the absence of hardware that would allow the subject to assume the lineman's position and gain stability. During the use of both cage and foot-strap restraints, the maintenance boom was fastened to the mockup and provided an object for the subject to fasten to, stand on, or hook around with feet and legs. This boom was not available to the subject during the rigid leg restraint tests. A locking rigidity at the mockup connection would have improved the positioning stability of the leg restraints. Many of the faults of the rigid leg restraints may possibly be overcome by proper redesign. One major difficulty which is inherent in the concept is the necessity for repeated reconnections of the restraint in order to encompass a work area of even medium dimensions. Figure *5-7* shows two instances of the subject's losing control while using rigid leg restraints.

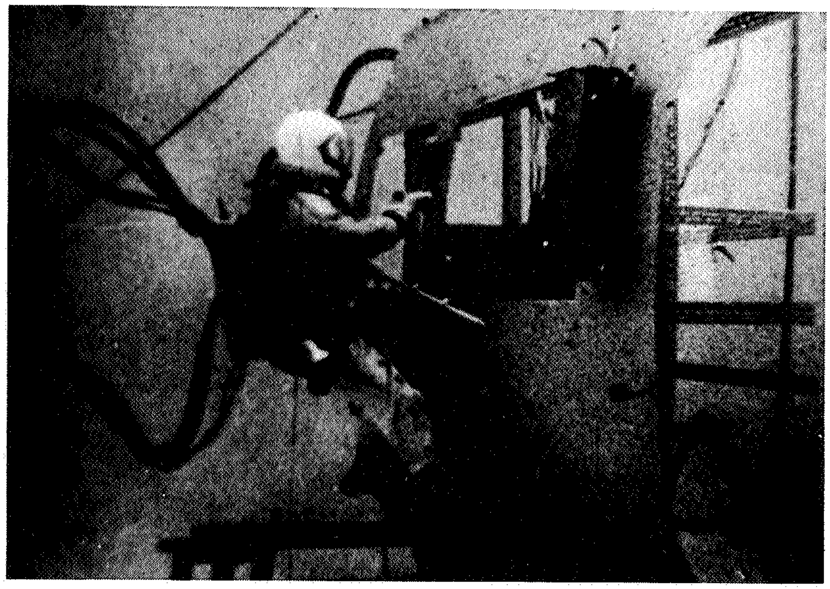


WORKING WITH ONE HAND

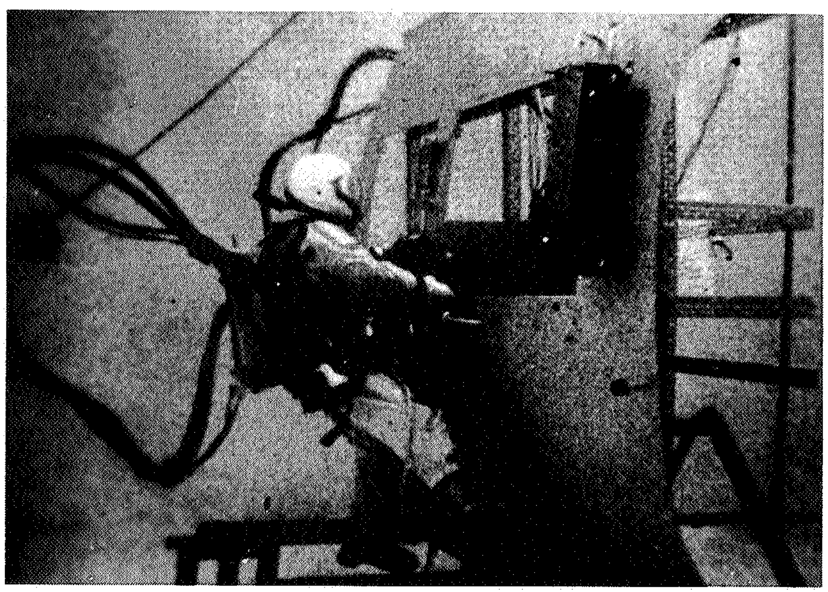


USE OF LEG FOR STABILITY F-7292

Figure 5-3



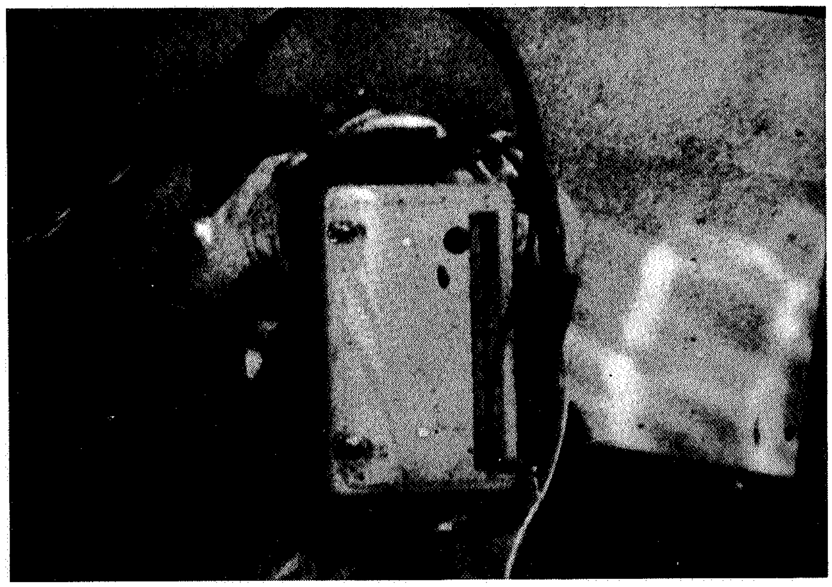
BUTTING TOES AGAINST SPACECRAFT MOCKUP



F-7293

"FALLING" FROM TOE BUTTING POSITION

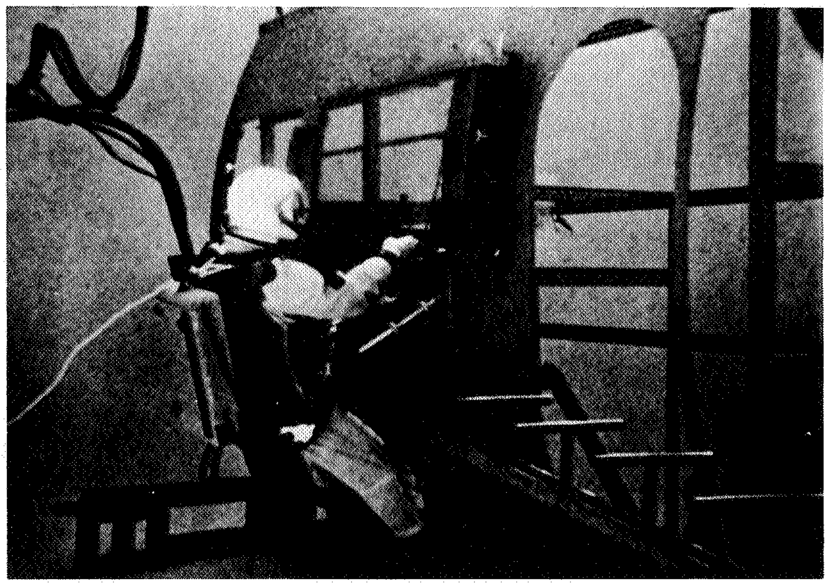
Figure 5-4



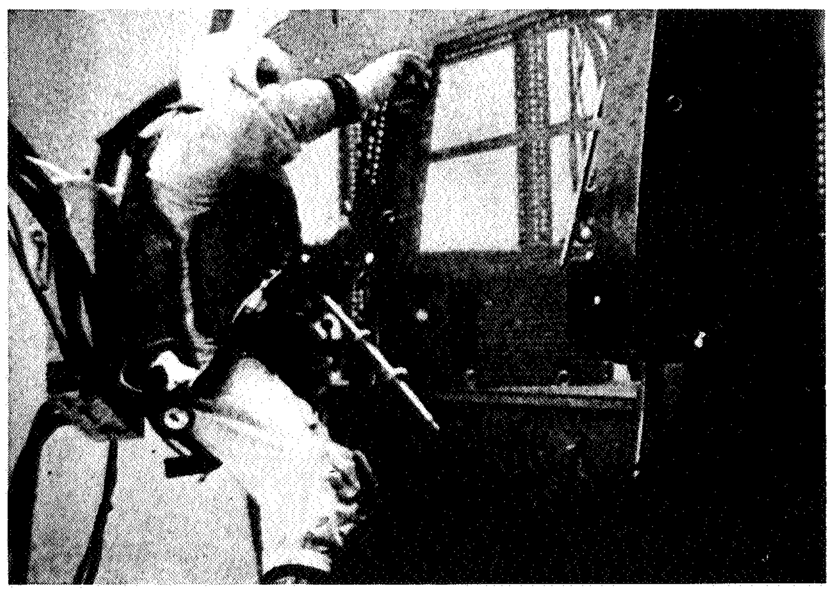
F-7294

WEDGING HEAD UNDER TOP EDGE OF ACCESS OPENING

Figure 5-5



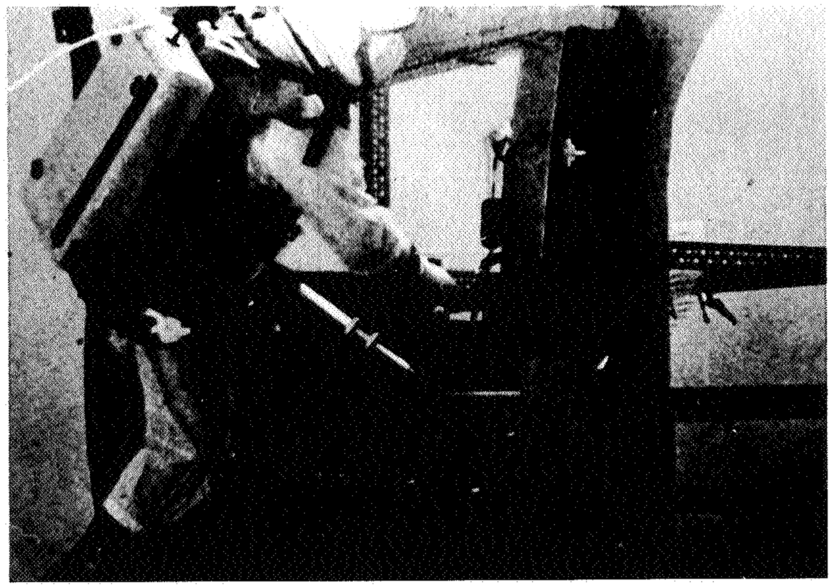
TWO LEG RESTRAINT



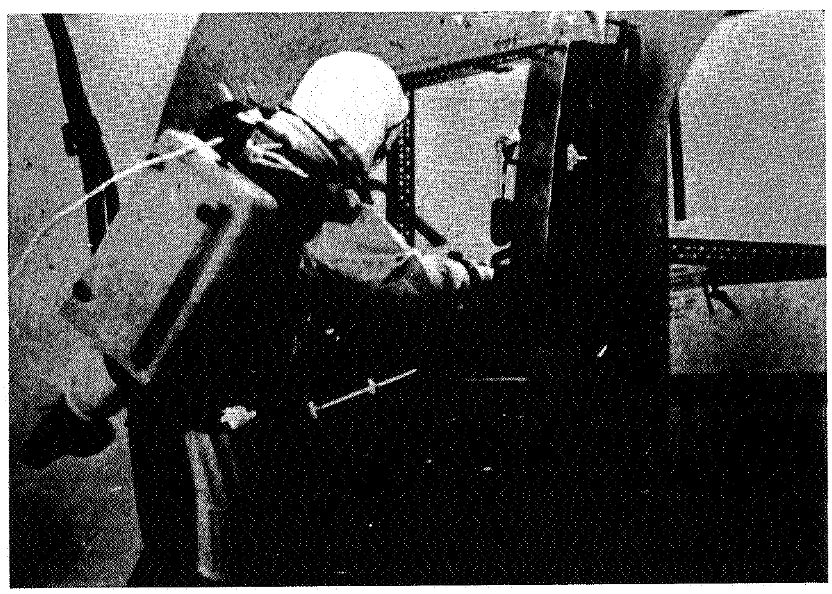
F-7295

MOVING TO ONE SIDE WITH ONE LEG RESTRAINT

Figure *5-6*



POSITION WITH ONE LEG RESTRAINT



F-7296

BREAKING ONE LEG RESTRAINT FROM ABOVE POSITIONAL FORCES

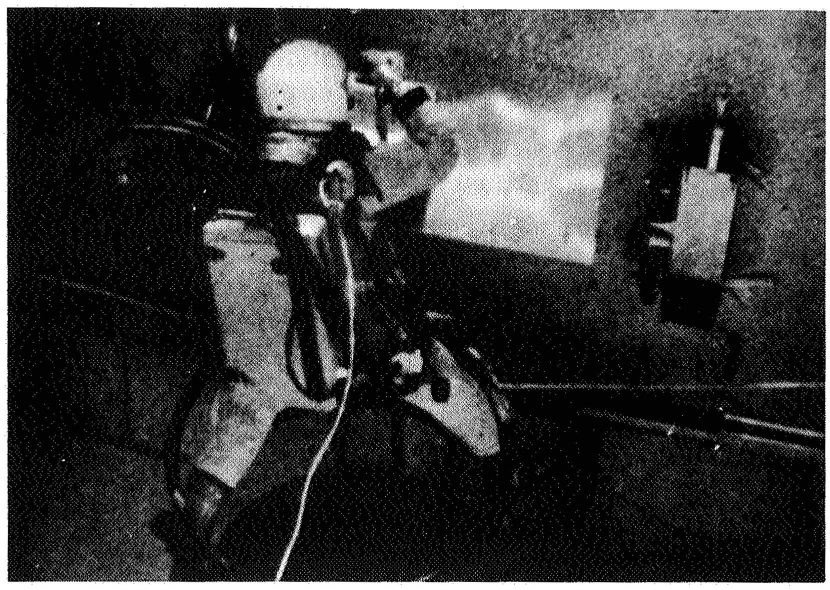
Figure 5-7

The difficulty encountered with the rigid leg restraint configuration during the maintenance tests was evidence enough to conclude that it was inappropriate in Its present design to be functional for the large modular erection tasks. Therefore, no attempt was made to test the rigid leg restraints in the tests for the beam erection, folding panels, two rigid modules, and the inflatable module. It must be painted out that the original rigid leg restraint concept that was considered at the time the tests for this study were being structured never materialized. The rigidity required was never obtained, so some of the negative aspects of the rigid leg restraints must be attributed only to the ones tested, and not carried over to the concept of rigid leg restraints in totality. Unfortunately, this program did not allow for the continued evolution of these restraints by design and development.

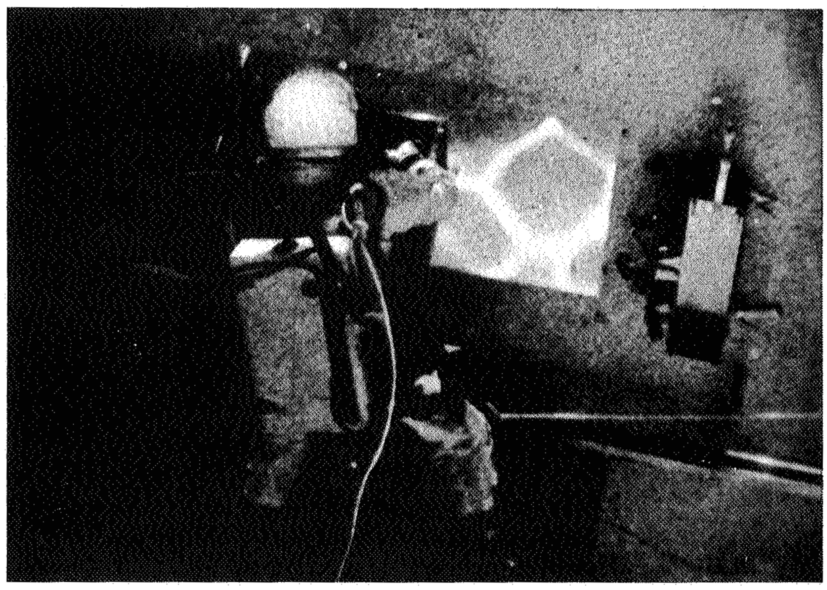
Cage Restraint

The original intent of the cage restraint was not completely carried out in the cage restraint tests because of lack of funds and time for design evolution. The concept for the cage restraint was based on the subject's being confined, but free to turn and to move up and down. It was assumed that the subject, by scissoring his legs, could bind and hold himself in the cage (Figure 5-8). It was also assumed that the subject, while in the free condition within the cage, would never be far (6 to 8 in.) from the circling enclosure. Thus, he could turn and move freely, but by small leg motions catch and contain himself within the cage. The tests conducted with the cage designed and used have not invalidated this concept, although it did not fully meet this design objective. It was far too large to provide the subject with this scissoring ability (Figure 5-8). The attempts by the subject to use this scissoring technique turned out to be not a binding force by spreading the legs, but rather a "spread eagle" effect to reach the sides of the cage. In this position, the subject had only two small points of contact and could exert very little force to hold himself in the restraint (Figure 5-9). To compensate for the largeness of the cage restraint, a strap restraint from the front of the subject to the top rung of the cage was added. The original intent of this strap was to keep the subject from ascending out of control to the surface if he should become positive in buoyancy during the test. This combination turned out to be unexpectedly efficient in that the actual position most oftentaken was to push against the strap with both feet either on the floor of the cage or standing on one of the cage rungs. When assuming this position, the subject was quite stable. This was the lineman's position: pushing against a holding device at the waist by forces exerted through the feet (Figure 5-9).

In addition, the subject utilized the cage restraint as a holding device for his feet by hooking his feet over and under the top two rungs (Figure 5-10). He was frequently riding the top rung by straddling the top rail (Figure 5-10). This provided the subject with a considerable amount of up and down movement, as well as movement from left to right, without manipulating a restraint connection. The left and right mobility



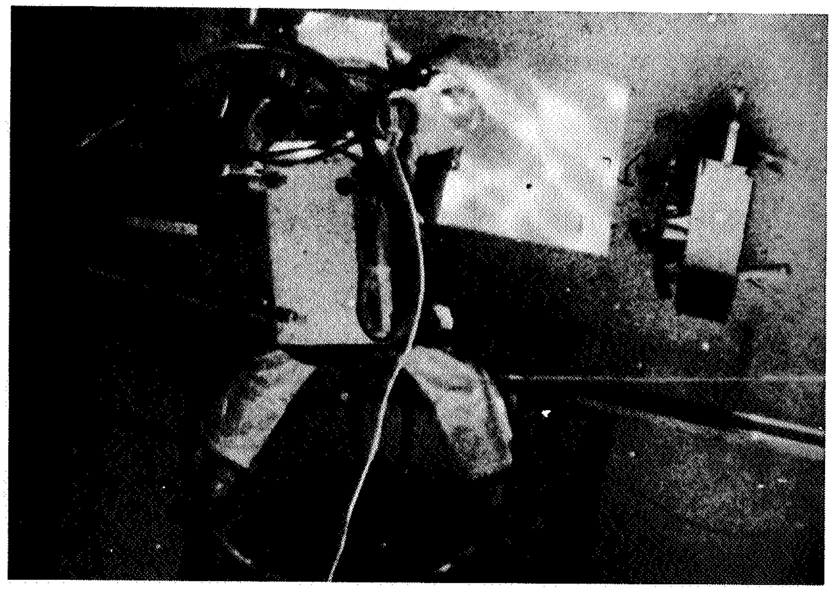
SCISSORING LEGS FOR POSITION IN CAGE RESTRAINT



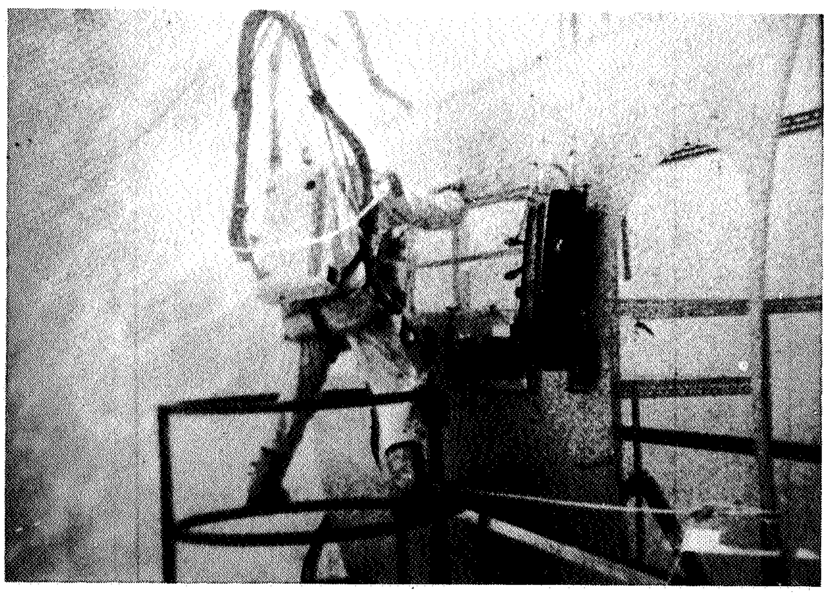
F-7297

"FALLING" FROM ABOVE SCISSORING POSITION

Figure 5-8



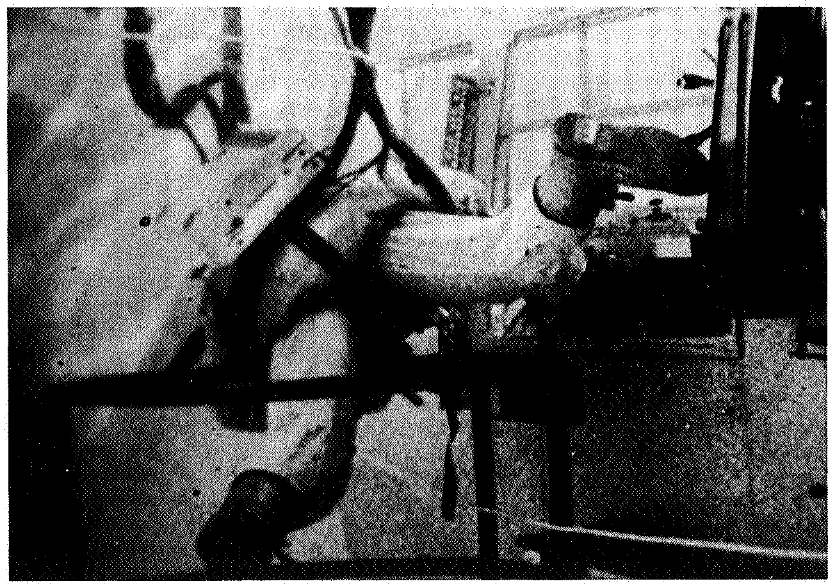
"SPREAD EAGLE" TWO POINT LEG CONTACT



F-7298

LINEMAN'S POSITION ON SECOND RUNG OF CAGE RESTRAINT

Figure 5-9



SUBJECT PREPARING TO HOOK A LEG UNDER
THE TOP RUNG OF THE CAGE RESTRAINT

F-7299

SUBJECT STRADDLING TOP RAIL OF CAGE RESTRAINT

Figure 5-10

requirement was solved by the subject's tipping considerably to the left or right, and sometimes actually taking a horizontal position (Figure 5-11). During these maneuvers, the subject would get a foot or leg bound in, around, or under one of the top two rungs of the cage to hold him in the desired position.

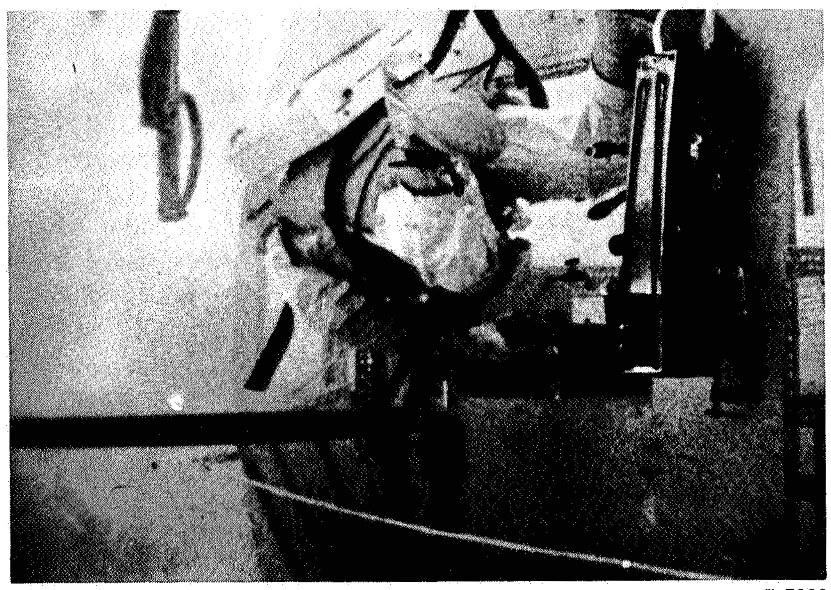
Considerable time was spent by the subject trying various positions for performing the tasks. These movements seldom required extending or shortening the flexible strap connected to his waist, but mostly seeking means of hooking or binding his legs for the best "hold." By getting a good hold with the legs, the subject was able to use two hands to perform the tasks, an accomplishment not frequently evident in the use of the one and two-leg restraints (Figure 5-12).

There were several joints and connections holding the cage on the maintenance boom. Each of these provided some slack, so that when the cage was in position and locked it still tended to flop around. This flopping or bouncewas reflected every time the subject moved, and of course there was feed-back from this lack of solid attachment. Thus, positioning tools to bolts was difficult, the tools slipping off easily as a result of cage movement. Generally, however, the subject performed tasks quickly and effectively. This is largely attributed to his getting into the most effective position to do the work. Once, for example, the subject had his legs straddling the top rung of the case and his head wedged up against the top edge of the access opening while working in the spacecraft mockup.

The subject shifted around a lot in the cage restraint configuration getting to positions and tools. These movements appeared to be a type of controlled tumbling: the subject getting where he wanted to go by falling there by pushoffs or pulls different from those used in conventional traversing. Although this technique lacked grace of movement, it was functionally effective.

Removal of the pipe segment in the hard task sequence was a difficult job for the subjects to perform. A considerable amount of force had to be exerted by the subject. Using the top rungs of the cage restraint, the subject turned to his side in a semiprone position, engaged his feet and legs in the upper portion of the cage, and removed the pipe segment. This type of flexibility using the cage restraint was evident throughout the three maintenance test levels.

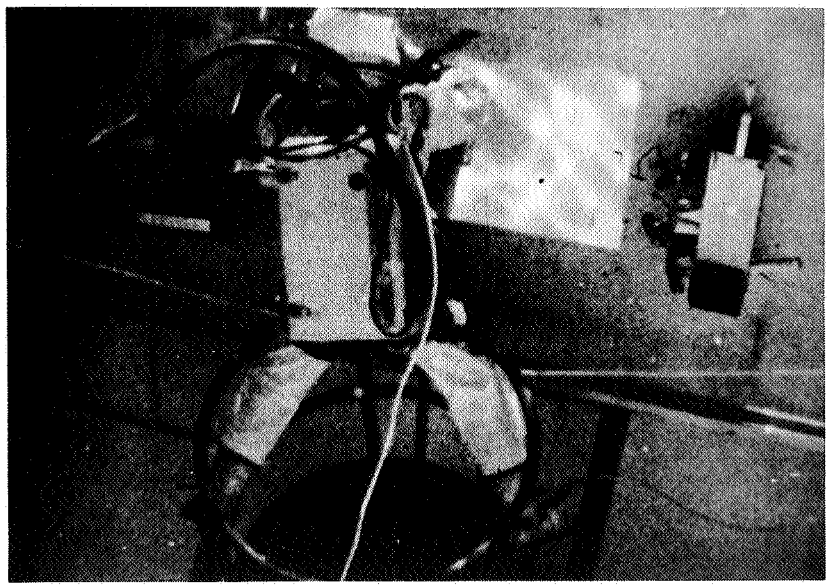
As the tests progressed, the subject continued to demonstrate new ways of performing the tasks (compared to previous restraint modes). Many of the positions assumed were lying on one side or the other. The advantage of turning 90 deg to the access opening seemed to be that if allowed a straight-down approach of the arm into the maintenance box area (Figure 5-13). Orientation of the cage parallel to the access opening would have been an interesting variation. At times, the subject was completely out of the cage in this horizontal position, with only his lower arm hooked under and around the top rung of the cage. The subject returned to the lineman's position frequently, getting a three points of contact by placing his feet on the



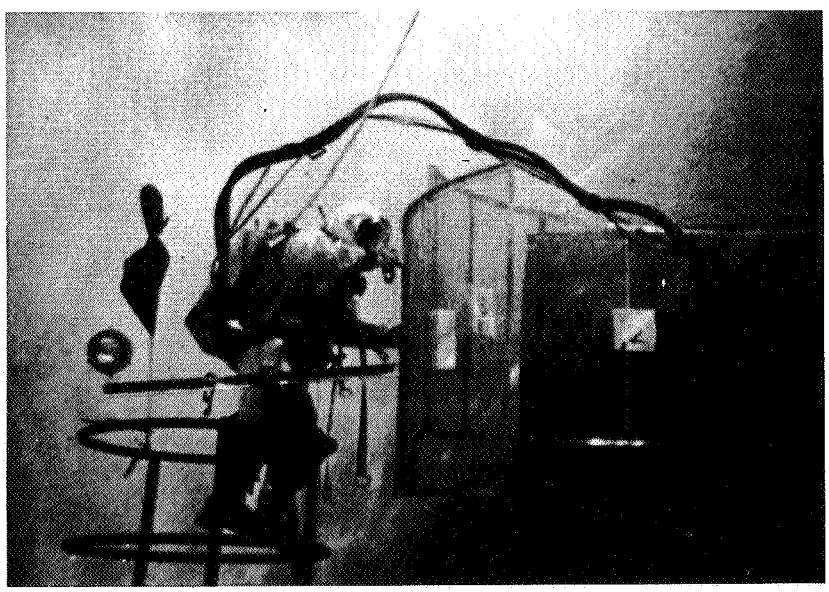
F-7300

SUBJECT IN HORIZONTAL POSITION TO REMOVE PIPE SEGMENT

Figure 5-11



SUBJECT USING LEGS TO MAINTAIN POSITION SO THAT
BOTH HANDS CAN BE USED TO PERFORM WORK

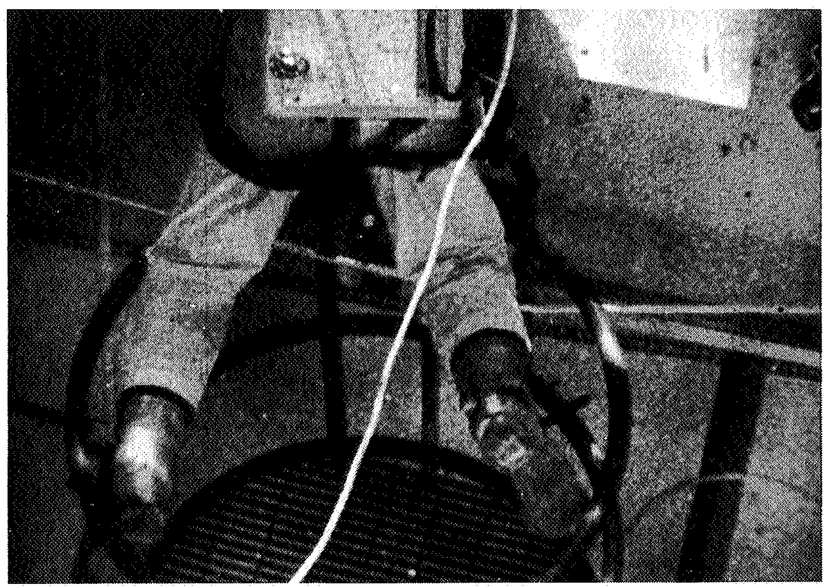


F-7301

SUBJECT USING LEGS TO MAINTAIN POSITION SO THAT
BOTH HANDS CAN BE USED TO PERFORM WORK

Figure 5–12

STRAIGHT DOWN EXTENSION OF ARM IN MAINTENANCE BOX AREA



F-7302

SUBJECT PREPARING TO OBTAIN "HANDS-AND-KNEES" POSITION IN ACCESS OPENING

Figure 5-13

second rung of the cage and applying leg pressure upward against the strap waist restraint. One innovation taken by the subject was to alter the three-point lineman's position to a hands-and-knees position (Figure 5-13). The subject placed his upper torso into the access opening supported by his arm on the shelf in the mockup. The knees were placed on the top rung of the cage and, by pushing up with his hand, the subject placed tension on the waist restraint and got a very firm position. The big advantage of this position was that it allowed the subject to work without having to forcibly overcome the suit resistance. More specifically, this placed the free arm in the natural position taken by the pressurized suit. A disadvantage of this position was that it tended to position the subject in such a way that only one hand was free to perform the task.

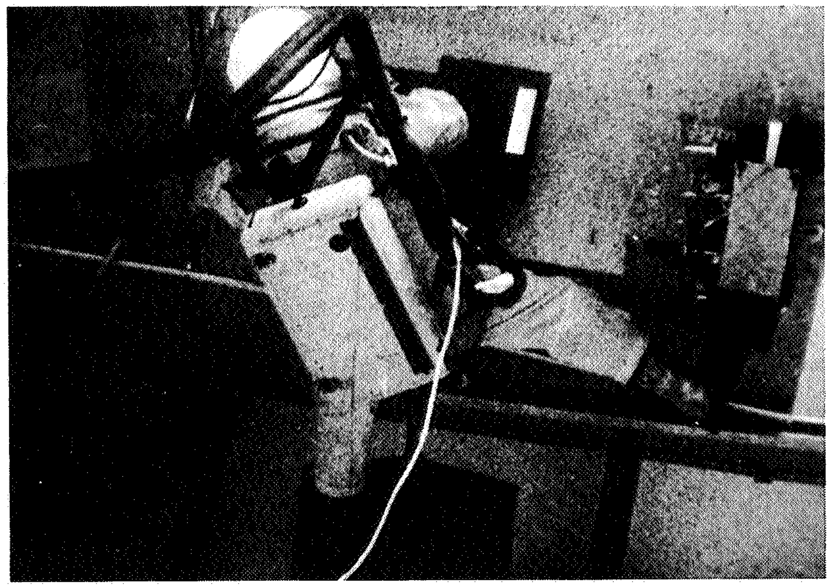
It appears that when the subject was well restrained and positioned to this work such that he could brace against the restraint with one or two contact points from the legs or arms, the task was accomplished with relative ease. Task performance difficulty was encountered when a stable position could not be maintained.

Foot-Strap Restraint System

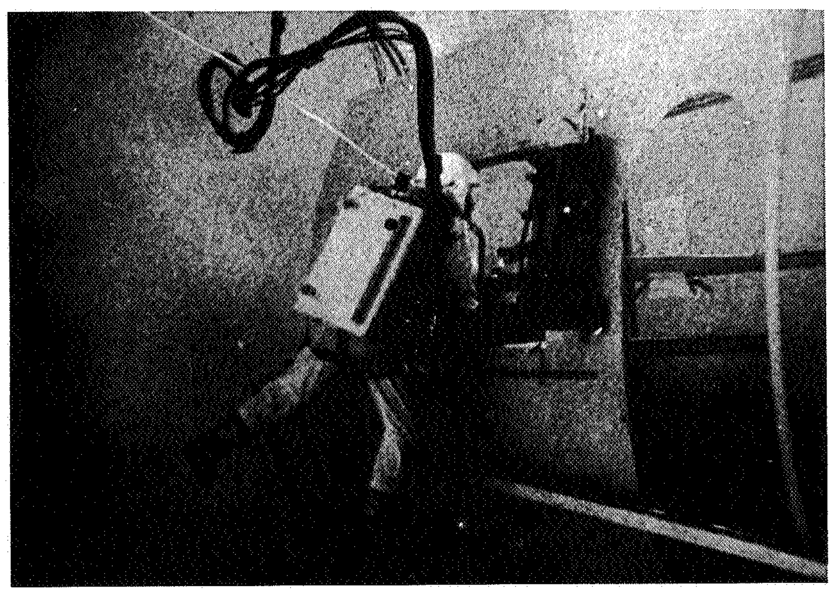
The lineman's position, so often taken during the cage restraint modes, was used almost exclusively during the foot-strap restaint modes. There are two reasons for this occurrence: the hardware configuration was such that this position was provided as a consequence of its use, and the lineman's position was the most effective posture available to the subject. The foot-strap restraint system consisted of a platform with two "hoops" for the feet and a tethering strap.

The foot-strap restraint system used throughout the tests appeared rather primitive after seeing films of NASA's "dutch shoe concept," developed for the Gemini flights. The more elementary system provided the subject a greater degree of torso flexibility, however, allowing him to turn left and right and thus adding to his visual and positioning capability without intertask restraint changes. The more primitive concept also allowed the subject to get far left or far right of the stationary restraint platform; this was accomplished by putting the right foot in the left foot restraint stirrup, or vise versa, and stepping out with the free leg. This provided a spread eagle posture, the subject holding on to the spacecraft mockup with the same hand as the foot inserted in the restraint system. This technique was repeated by the subject again and again throughout the foot restraint tests (Figure 5-14).

The one-handed tasks appeared to be done with greater ease and quickness in this restraint mode. This is attributed partially to learning, but mainly to the improved position obtained by the subject. For example, the rigid leg restraints held the subject away from his work while the foot restraints allowed the subject enough flexibility to adjust the distance to the work spot and move closer to his work (Figure 5-15).



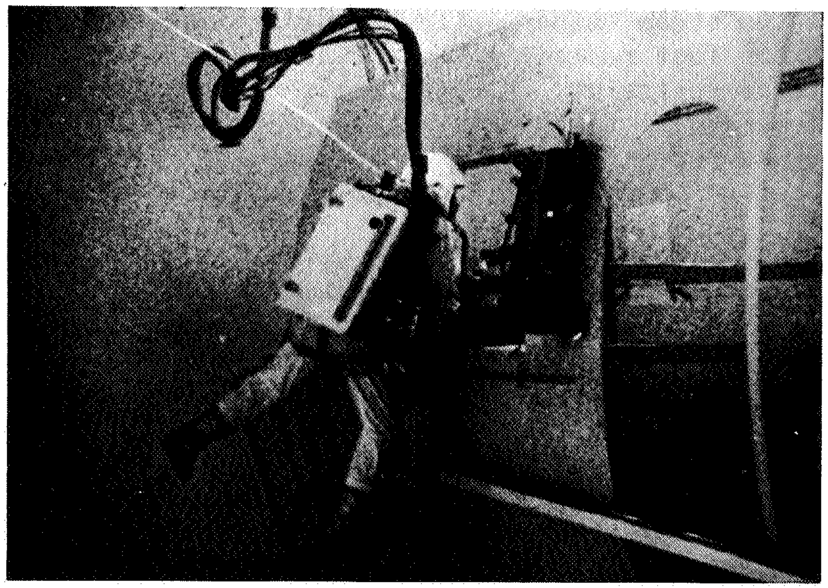
"SPREADEAGLE" POSITION FROM STRAP-FOOT RESTRAINT



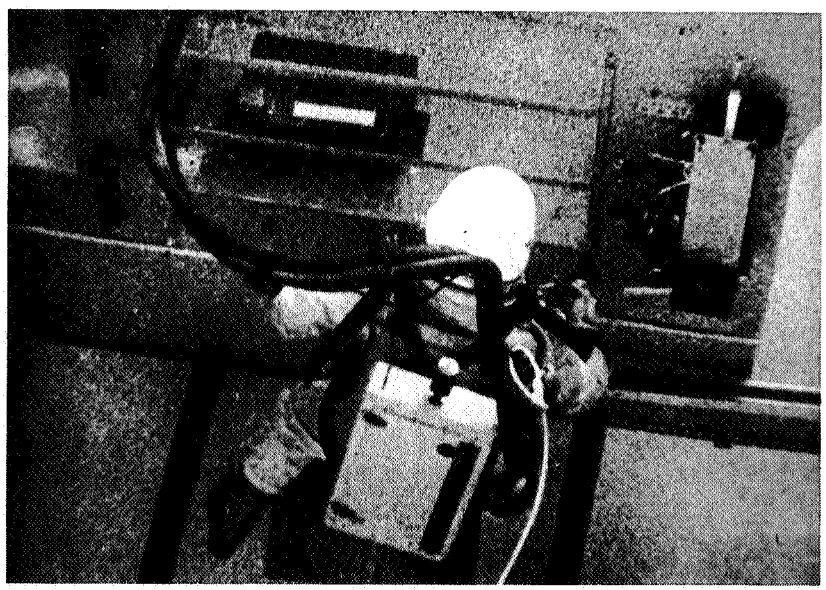
F-7303

SUBJECT WITH OPPOSITE FOOT IN STIRRUP AND "STEPPING OUT"

Figure 5-14



SUBJECT MOVING CLOSER TO WORK FROM STRAP-FOOT RESTRAINT



F-7304

SUBJECT REPOSITIONING HIMSELF WHILE USING STRAP-FOOT RESTRAINT

Figure 5-15

The use of the strap tether, attached at the subject's waist, in conjunction with the foot restraint, was relied on more than it had been while using the cage restraint. However, this does not necessarily imply that it was more essential to the foot-strap restraint opertions. The waist connection was necessary in both cases and the task sequences could probably not have been completed without this additional restraint aid.

The freedom of body movement allowed by the foot-strap restraint provided the subject with the previously unavailable work position of squatting. This position was used by the subject to get to the lower fasteners on the access panel. Crouching to his work improved his vision at the work place, and tool contact seemed to be better than in the same task from an upright or lineman's stance.

Based on observations of all of the maintenance tests, the human engineer concluded that the foot-strap restraint system was one of the best configurations tested. This conclusion does not imply that it is, however, the best of the concepts. Design faults existed in each system. In each case, design changes would change the effectiveness of the restraint system.

Gemini XII Type of Strap Restraint

One maintenance test was conducted with a Gemini XII type of strap restraint. Their advantaqe of this system over the rigid leg restraints was readily apparent. One of the major complaints reported by the subject when using the rigid leg restraints was the necessity to continually disconnect from and reconnect to the eyebolts on the spacecraft so that movement from one work place to another could be accomplished. Although this was not completely eliminated with the strap restraints, the connecting and disconnecting was greatly reduced. The Gemini XII type of strap restraints also allowed the subject to "belly-up" to any work area; if he wished to remain in the close position, he simply had to shorten the strap by pulling on a D-ring.

An attempt was made to observe the use of the Gemini XII type of strap restraints without the cage or the foot-strap restraint hardware during the large module assembly tests. Since connecting points had not been placed on the large modules, it was necessary to provide restraint attachment capability on the maintenance boom. The attachment consisted of an upright that could be moved along the boom and locked in place at any selected location. An adjustable cross beam was placed on the upright with connecting eye bolts spaced at 12-in. intervals along its 4-ft length. The hardware was a T-design. The top cross member could be removed and repositioned; this allowed the top member to be either parallel or at a right angle to the maintenance boom. The use of this configuration was not nearly as functional as the cage or foot restraint devices. The subject used the maintenance boom to position his feet in much the same manner as he had done using the bottom of the cage and the plate of the foot-strap restraint (Figure 5-16). In this manner he could partially use the resultant more stable position. On occasions, the lineman's position was assumed. This was a difficult position for the subject to maintain because of the small area available for his feet (Figure 5-16). The top of the maintenance boom was too small to provide an area adequate for both feet at the same time. The subject also had trouble finding the boom with his feet and maintaining contact with it. This resulted in considerable stumbling, slipping, and fumbling with the feet to obtain and maintain position of the contact, Compared with the cage and foot-strap restraint, the T-bar configuration was less functional and less adequate, the main difference being one of securing and holding the feet on the hardware to assist in maintaining a stable work position. Strap restraints actually have no functional advantage in providing a better work position than rigid leg restraints unless the straps are associated with hardware the subject can put his feet on. When hardware for foot placement is available, the advantage of the flexible straps connected at the waist is apparent. The freedom of movement of the straps over the rigid leg restraint is considerable.

As a result of this study, the energy expended by the subject in manipulating restraints and overcoming poor positioning problems as a function of a given restraint is one of the most important factors to be considered.

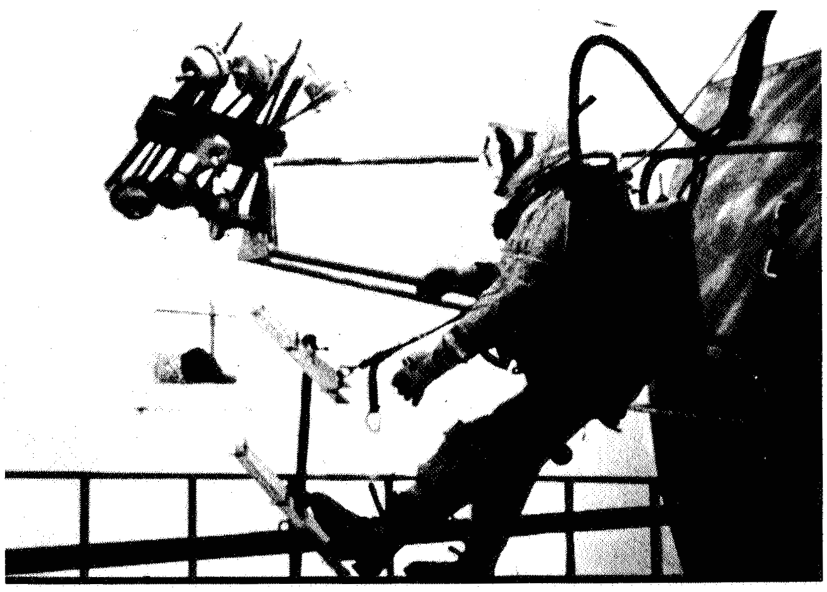
TOOL SELECTION

Early in the EVA program, when consideration was being given to designing an experimental study that would represent typical maintenance tasks expected in future space exploration, the problem was posed as to what tools would be used in conjunction with the maintenance tasks selected. The tool contingency influenced the final selection of maintenance tasks in that tools were selected by considering the basic functions of hand tools and the manner in which the operator uses them to perform work. These considerations are listed below.

Tool Function	Operator Function
impact	striking
turning	torquing
cutting	push/pull
prying	pressure
holding	hold

From these functions, a list of eight representative tool types were selected (Table 2-1). Several specific tools were then chosen that met the requirements of each tool type.

FEET CONTACT WITH MAINTENANCE BOOM "T" HARDWARE



F-7305

LINEMAN'S POSITION FROM "T" RESTRAINT

Figure 5-16

It was believed that this approach would provide the study, within its limitations, as broad a sampling of hand tools as possible without causing a deemphasis of other important aspects.

TOOLS

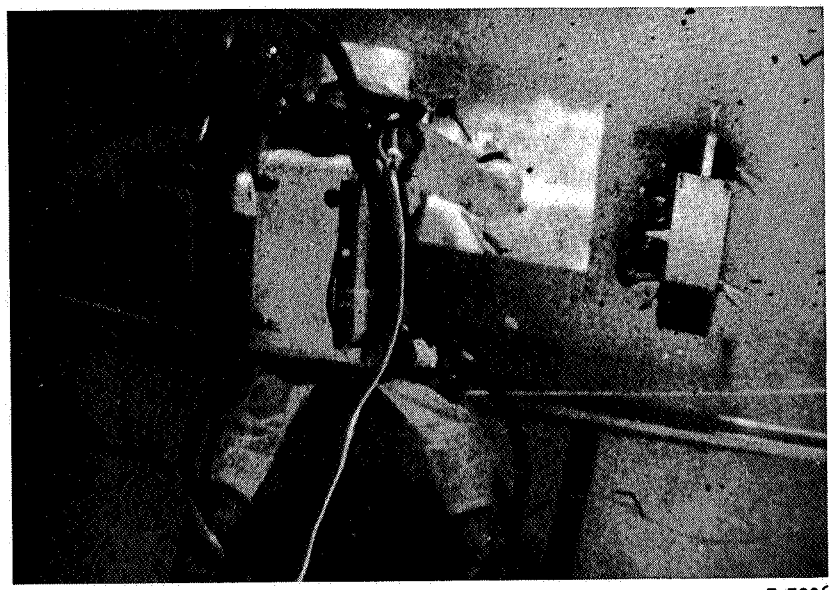
Hammer

The hammer test consisted of striking from above a punch placed near waist height and directly in front of the worker. Two hammers were used: an 8 oz and a 12 oz. A third hammer, 24 oz, was deleted after preliminary test as too large and awkward to use.

Directing the hammer to its point of impact, although successfully performed, was a task of some difficulty. The suit resistance made performance awkward. On occasions, the subject struck glancing blows off the punch. During one-g testing, the task was bypassed on several occasions., The task deletions were a result of the subject's being unable to get positioned to strike the punch from above. This is revealing in that it points out the necessity of one getting close to the work from a frontal position, and of being somewhat above the striking point when in a pressure suit to properly execute a hammer blow.

In the underwater simulation (Test 1.2.4.4.), the subject solved the positioning requirement for the task by getting the striking point about waist high, close to his torso, and by placing his head into the access opening (Figure 5-17). Similar positioning was assumed for the same task in Test 1.2.5.5.

From the tests, it was concluded that both hammers used were acceptable for striking tasks that do not require a considerable amount of force. The dexterity exhibited in the task was largely a function of assuming an appropriate work position to place the striking zone approximately waist high and within a 12-in. distance from the front of the subject. Although overhead striking was not attempted in the tests, it is assumed that such a task could only be performed with great difficulty, if at all. This conclusion is based on extrapolation from performance of overhead tasks with other tools and the difficulty encountered by the subject in performing the overhead tasks in general.



F-7306

USING HAMMER IN ACCESS OPENING

Figure 5-17

Clamps

The need for effective fastening and clamping of objects for EVA is obvious, since the necessity exists to restrain all removed and/or unfastened hardware. A review of common clamps now in existence did not reveal a clamp that appeared to have the universal application required by the variety of clamping tasks in the maintenance tests. The clamps used for testing were selected with the assumption that they were representative of clamps simple enough to operate and still applicable to the tasks.

A major problem with all clamps, anticipated prior to testing and substantiated throughout the tests, was the requirement for two hands to manipulate the fastening mechanism while holding the object to be fastened in the desired position. (The exception to this was the spring loaded clamps which have little holding capability.) Two-hand manipulation of a clamp left the worker with no way of holding the object to be fastened. If he held the object to be fastened, he was forced to manipulate the clamp with one hand (Figure 5-18). The latter procedure was the one used by the test subject almost without exception. When the subject was successful in completing a clamping task, it was usually accomplished by taking advantage of gravity to maintain the position of the object being clamped. When neutral buoyancy of the object prevented the use of gravity, the task was either deleted or performed by a diver, since the subject could not manage both the neutrally buoyant hardware and the clamp at the same time.

The spring-loaded, plier-type clamp was manipulated with one hand and was effective for small objects of light weight. The lanyards with snap ends proved more effective than the spring-loaded clamps because the subject could operate the snaps with less difficulty and more speed.

The failure of the subject to perform the tasks of clamping the tool kit and the access panel to the mockup required their being eliminated from the task sequences. The difficulties encountered in the clamping and hardware manipulations as a simultaneous task were so extreme that it would have abused the subject to continue testing this task.

If the tasks selected for testing are representative of maintenance tasks and represent in some considered degree the maintenance tasks that may be anticipated as scheduled tasks for EVA, then positive locking clamps that may be manipulated and engaged with one hand are a mandatory hardware development effort.

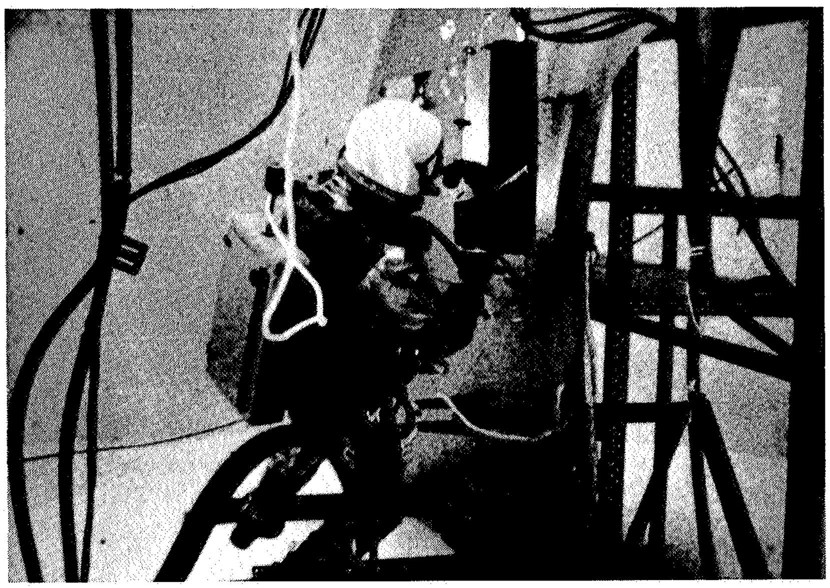

F-7307
SUBJECT ATTEMPTING TO MANIPULATE A CLAMP WITH ONE HAND

Figure 5-18

Pliers

The plier type of tools were defined to include tools that are activated by the operator with a pinching motion, such as wire strippers, bolt cutters, vise grips, and some pincher-type clamps.

The pliers were used in the maintenance tasks to hold and position electrical wires, to cut electrical wires, and to bend the wires to appropriate shape for fitting to electrical connecting points. Most of the tasks were of short duration. Once the operation was started, the task was usually accomplished without difficulty. The problem appeared to be getting the tool fitted to its work spot and properly positioned in the hands. Considerable fumbling was usually associated with the pliers in the pretask activity. To the known problems of feedback through the pressurized gloves, the visual observation, and the requirement for a steady position, we must now add the problem of tool shape. Most of the plier tools required the handles to be swiveled apart further than could be accomplished with one hand and still engage the tool. To overcome this one-hand manipulating difficulty, the subject generally used his other hand to position the tool in the operating hand while at the same time engaging it at/on the work spot. Thus, a one-handed tool became a two-handed tool during the test situation (this was true for the suited one-g tests as well as for the water immersion tests). The vise grip clamps were the most undesirable in this respect, and a modification of them was made to keep the handles from separating to such a large "throw." The modification also reduced the jaw travel when engaging them, and required a very fine adjustment to get a good tight grip when locked. Thus, the modification replaced one problem with another of equal undesirability. If modification to plier-type tools are to be made, it is suggested that a ratcheting mechanism be used so that repeated squeezing will engage the tool.

Prior to testing, the vise grip had been considered an ideal off-the-shelf hand tool for EVA because it gave a strong positive lock and could be positioned and engaged with one hand. This did not prove to be the case, and in nearly all tasks requiring the use of vise grips the subject had great difficulty and frequently required the assistance of a diver to help make the connection. The clamping tasks usually required one hand to hold the object to be clamped and one to manipulate the tool, preventing the subject from using two hands to work the tool. This incident of what was thoughtto be a well-conceived concept for maintenance failing in actual application is a relevant example of the effects of the weightless environment. It is recommended that all EVA assembly and erection concepts be tried and proved by simulation to assure the elimination of unknown contingencies of this type.

One of the fine dexterity tasks consisted of using a plier-type wire stripper. Across the blade of this tool, a distance of about 1/2 in., were four openings for wire sizes 10, 12, 14, and 16. The subject was required to place a No. 12 electrical wire in the third opening and engage the tool to remove the insulation from the wire. A placement error of as little as 1/16 in. would keep the tool from removing the insulation and would require repositioning the wires and trying again. The successful completion of this task was always dependent on the subject's being able to get a stable position that could be maintained. This would allow him the freedom of both hands to accomplish the task. Even so, the preparatory work of getting the wire, the tool, and the upper torso just right was a time-consuming activity for the subject. Once these conditions had been met, the task was accomplished. Seldom was the task accomplished without several attempts being required to get the wire properly positioned in the tool.

This particular task generated considerable comment among the EVA team members and the sbbject. The question was posed as to the advisability of including the wire stripping task as part of the maintenance tests since its dexterity requirement was so fine that the possibility of the subject successfully performing the task was indeed remote. The task was successfully accomplished and established that tasks requiring relatively fine work could be performed if proper positioning and stability was provided.

Performance using the pincher-type bolt cutters was always very good. The primary reason for this occurrence is that when the cutters were positioned on the work spot, a small amount of pressure on the handles of the tool engaged the jaws enough to allow the operator to transfer the stabilizing dynamics of his position to his hands on the tool. When the subject applied pressure, the tool itself became the object of stabilization until the cut was completed. When the rod being cut separated, the subject almost always lost control and "fell" from the position. The cutting part of the task always went smoothly once the subject had started to apply pressure to the handles of the tool.

The remaining pliers were all operated very adequately within their expected capability, the exception being the handling and manipulation problem with pressurized gloves. The typical problems associated with positioning, stability, and restraint devices existed as it did for all tools and most tasks.

Hand Drill

Two types of drills were used during the tests: the standard carpenter's brace and a small hand drill. The diameter of the turning throw for the brace was 10 1/2 in. while only 6 in. for the hand drill. The task required the subject to drill downward from his position. This placed throw for the hand drill in a vertical plane and the brace throw in a horizontal plane.

Task completion with the hand drill was accomplished only when the position assumed by the subject allowed two or more points of positioning contact. The work spot was approximately 10 in. inside the access opening. One of the favored positions for this task was to place the head inside the upper edge of the mockup and use the back of the head as the second point of contact to maintain the position (see restraints coverage for detailed duscussion). In such a position, the subject could maintain a rhythm on the activating lever of the tool. In other positions, the necessity to continually open the tools lever tended to create an unbalanced condition that lacked stability. The subject could not maintain the turning rhythm when not stable and the bit would bind and stick. A successful completion of a drilling task was always a function of a secure and stable position for accomplishing the work.

The carpenter's brace was never used to a satisfactory task completion. Eventually, the carpenter's brace was dropped from the tests and only the hand drill used. The subject failed to perform the drilling task with the brace possibly because of the large throw of the activating lever, a diameter of 10-1/2 in., and because of the horizontal plane of rotation of the lever when the brace is positioned at the work spot. An additional difficulty encountered with the brace was in the accessibility to the work spot, which was adequate for the hand drill, but not for the larger brace. A much greater volume of free space around the work spot was required for the brace to be properly operated. A frontal drilling task with the brace throw being activated in a vertical plane may have been possible, but was not included in the tests.

Saw

Two saw configurations were originally planned for the test: a typical hacksaw and a keyhole-type saw with a blade for cutting metal. During the one-g tests the keyhole saw was found to be unsatisfactory and was deleted from the remaining tests. The preference by the subject for the hacksaw was attributed totally to the teeth of the hacksaw blade, rather than to any functional difference in the saw configurations.

The depth of the analysis possible within the framework of the test situation does not provide a means of differentiating and comparing the differences of tools to one another unless extremes exist. The saw was not one of the extreme tools. It generally worked quite well for the subject if he was positioned firmly and could maintain the position for the task duration. Once again, positioning was essential to the task success. Where tool use involved muscular strength and repeated motions, the stability of the position over the duration of the task was necessary if the task was to be performed from beginning to end without interruptions. Interruptions in the sawing task were frequent. The most obvious causes of delay were the loss of position stability, fatigue in the arm used for the task, and the interruptions of the sawing motion rhythm.

Fatigue during the sawing task is attributed to factors additional to the actual physical effort of the sawing act, such as the detrimental effects of the pressure suit, limited vision, poor tactile feeling while wearing pressurized gloves, difficulty of getting and maintaining a good position to do the work, the restricted work place of the left hand side of the mockup opening, and restraint restrictions,

Attempts by the subject to perform the sawing task were frequently unsuccessful. In Test I.3.5.5., the successful completion of the task using the left hand is attributed to the good position obtained by the subject using the foot restraints. All attempts by the subject to saw left handed while using the rigid leg restraints were failures. The sawing tasks required firm, stable positioning for successful completion.

Files

The file was used to cut a notch in a bar, this notch being the starting position for the sawing task. The motion used to operate the file was essentially the same as that required for the saw, so it was classified as a saw-type tool. The task was very simple and only a few strokes of the file were required to cut the notch. Any difficulty that the file task provided was one of dexterity in the proper positioning of the file. Again, the success of the task was a function of the subject's position and stability. When difficulty was observed in performing this task, a positioning or stability problem was also observed. No attempts were made to file for smoothing or fitting, which are two common and frequent filing tasks. Therefore, it can be concluded that using sawing motions with a file to cut a notch presented no problems, but this does not mean that all filing tasks can be performed.

Punches

The punch was selected to represent that group of small hand tools that are held and struck. The two specific tools used in the tasks were a center punch and a blunt-pointed, drift punch. The observer was concerned basically with the ability of the subject to position the punch and maintain its position while being struck.

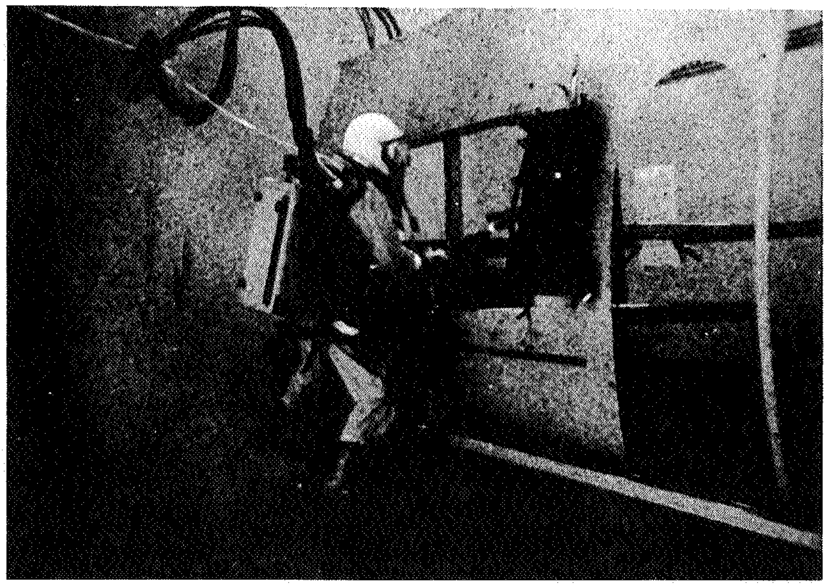
The successful completion of this task was not completely dependent on handling dexterity. The subject could position, hold, and strike the punch when the other related conditions would allow it. The failure to perform the task element was always attributable to secondary interferences, such as the subject being held away from the contact point for the punch by his restraint configuration, or the lack of a stable position from which he could work with both hands. To perform the task element, one condition had to be met: a stable work position--one that could be maintained and not disrupted by the body movements resulting from striking the punch with a hammer. In addition, the subject's position had to be one that allowed positioning of the punch and manipulation of the hammer. The position most often assumed for the tasks that were successfully completed was one in which the work area was directly in front of the subject about waist high.

Wrenches

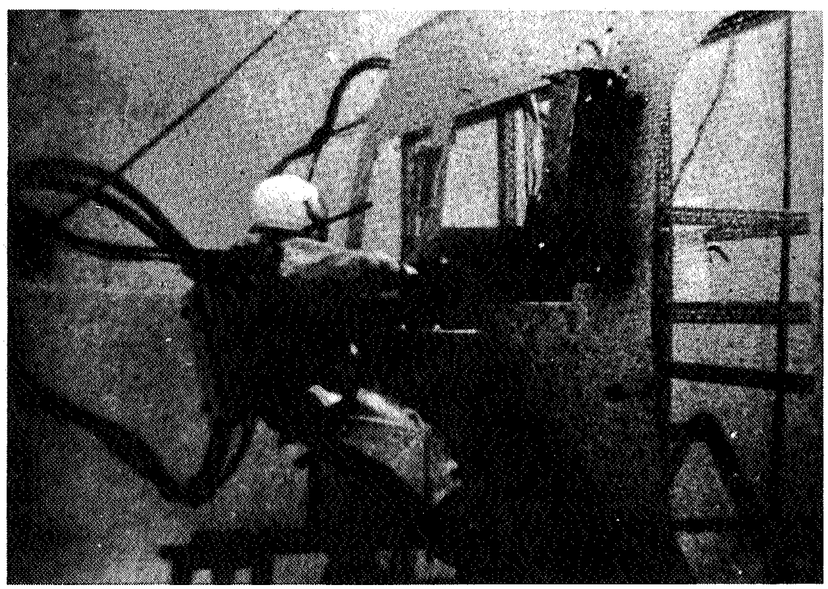
A considerable variety of wrenches were tested. There were two basic reasons for this: (1) the frequency with which wrenches are used in maintenance work, and (2) the possibility of identifying any existing differences that would make one wrench type more desirable than another.

The test situation was set up to include simple one-handed wrenching tasks and to proceed through difficult, high-torque, two-handed ones; the latter included both one-wrench and two-wrench manipulations. As part of the test situation, repetitive torquing of the same wrench was included. Thus, the wrench could be observed over a long period of time under various conditions. Again, as in all the tool-task situations, the conditions of position and stability were the dominant factors in the success or failure of task completion, Failure (degrees of unsatisfactory and undesirable performance) was always associated with the subject's having positioning and stability difficulties. When good position and stability were evident, all wrenching tasks were successfully performed (Figure 5-19).

Two types of adjustable jaw wrenches were tested: an 8-in. crescent wrench and two 10-in. pipe wrenches. Observations were made on both types used in tasks requiring both the use of one and two wrenches. Without exception, the two-handed wrenching tasks gave the subject great difficulty. With a wrench in each hand, the subject did not have a free hand to hold, correct, stabilize, and keep a good position from which to perform the task. An interesting example of positioning stability was observed during film analysis of the maintenance tests. The subject had tried several approaches of performing a two-handed task, but could not maintain either a steady position or get close enough to his work. He solved the positioning problem by placing an arm into each of the two access openings on the mockup and "hugged" himself to the dividing area between the two openings. His forearms held him in position, in conjunction with his restraint, yet both hands were relatively free to manipulate tools. This position did not allow him to move either of his hands any great distance since the forearms had to be kept in contact with the section of the mockup he was "hugging." It was in this manner that one specific two-handed task was performed. When such positioning innovations were not possible, or not discovered by the subject, the two-handed tasks frequently met with failure. To overcome the great difficulty of performing a two-handed task, the subject often found a method of using only one hand. An outstanding example of this technique was the use of two pipe wrenches to "break" a preset torque valve on a pipe union. The task was set up so that the subject would be required to place one wrench on the pipe to keep it from turning when the other wrench was turning the union to break the connection. It was intended that the subject perform this task with a wrench in each hand, pulling on one and pushing on the other, so that force would be exerted on each wrench as they come together in a pinching movement.



SUCCESSFUL WRENCHING POSITION



F-7308

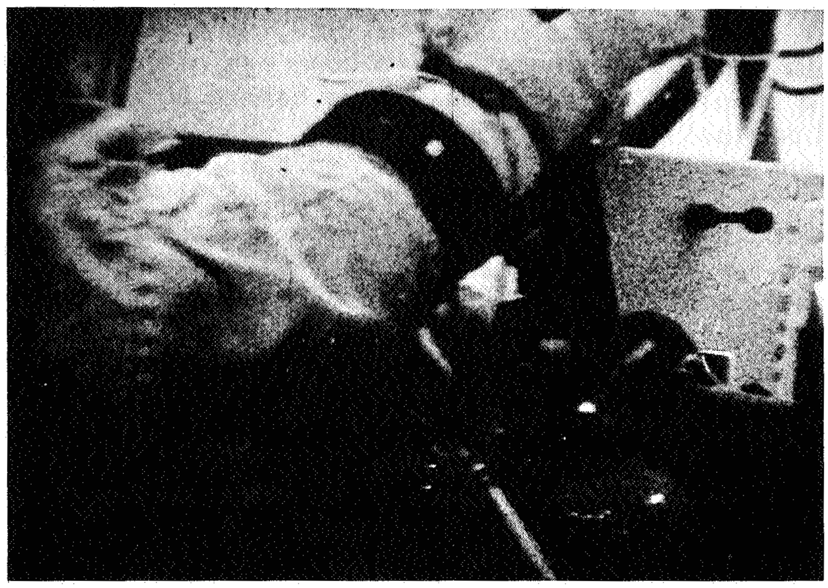
"FALLING" AWAY FROM RIGID LEG POSITION DURING WRENCHING TASK

Figure **5-19**

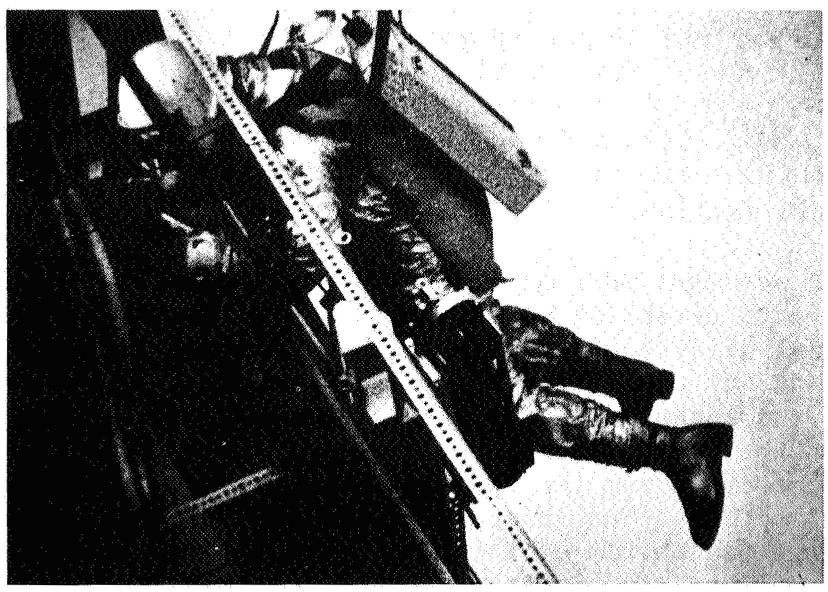
The subject first attempted to perform the task in this manner. In doing so he lost control of the wrenches by dropping them, fumbling the adjusting rings, or having the wrench slip off the pipe or union. Then, the subject discovered the process of wedging one of the wrenches while connected to the pipe by pressing it down against the mockup where it was held in place by friction. Then he had both hands free to adjust, fit, and manipulate the second wrench. When the wedged wrench was positioned, the subject could then use one hand on the unbound wrench and the other to stabilize his position (Figure 5-20). Actually, a two-handed task was broken down into smaller task elements that allowed the subject to perform the task with one hand in a series of steps. Work improvement of this nature was almost always attempted for two-handed tasks that proved difficult due to positioning stability. An exception exists to this breaking down of the two-handed tasks to one-handed steps, that is associated with the lineman's position. Discussion of this position and its effect on the work capability of the subject is covered in the section dealing with restraints.

Two socket-wrench configurations were used. One was with a ratchet handle (Figure 5-20), and the other with a T-handle. Both wrenches could be manipulated under ideal conditions with one hand. However, the normal use of socket wrenches is with the operator holding and guiding the wrench shank with one hand and torquing it with the other hand. The subject usually used the socket wrenches with one hand. The long extension of the tool, used to reach bolts that could be reached in no other manner, was a hindrance in the one-hand torquing due to the bolt contact point being too far from the controlling hand. Deviations of aim and bolt-wrench contact were more frequent as distance to the socket was increased from the hand holding the tool. There was a considerable amount of fumbling and difficult by the subject in making good, quick, repeated bolt-wrench contacts [Figure 5-21). The trouble encountered by the subject in making bolt-wrench contacts is also attributed to the lack of feedback through the pressure-gloved hand. (The ballooning effect of the gloves when pressurized, and other restrictions associated with them is, discussed under Recommendations at the end of this section.)

The socket wrenches were used in several combinations during the maintenance tests to establish possible utility in providing the astronaut with an assortment of interchangeable tools. Interchangeable tools would have the advantage of minimizing space requirements. The principal disadvantage of the socket wrenches used in these tests was the inadvertent disconnection of the tool. There were frequent cases of the socket wrench coming apart, sometimes from the tool kit when being removed, and occasionally during use. Such disconnections would result in part of the tool being lost at the bottom of the tank. The general awkwardness of the socket wrench configuration also contributed to other tools being knocked or pulled from the tool kit. Retaining devices were used on many of the tools, especially those of simple configuration that would lend themselves to lanyard attachment (Figure 5-21). The sockets and socket wrenches were not retained.



TWO WRENCH TASK REDUCED TO ONE WRENCH TASK BY WEDGING ONE WRENCH AGAINST THE SPACECRAFT MOCKUP

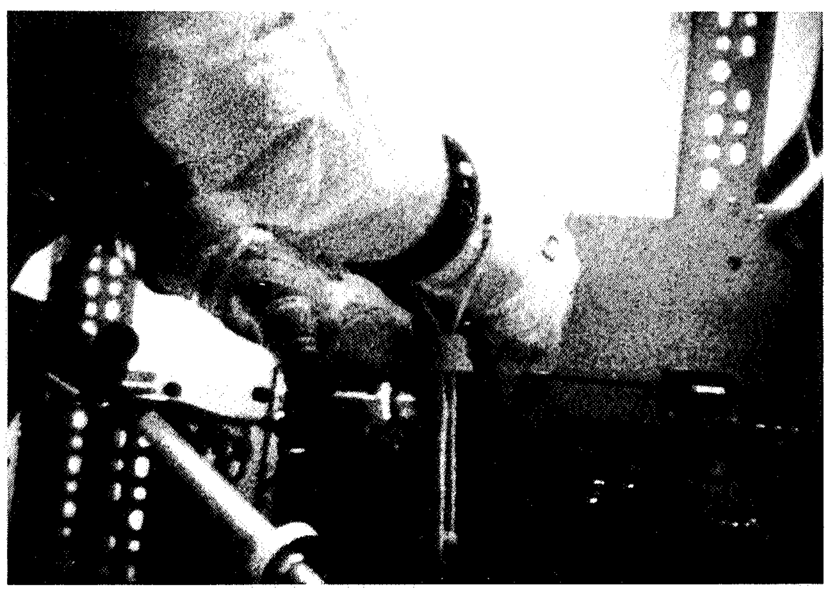


F-7309

TWO HAND APPLICATION TO RATCHET WRENCH

Figure 5-20

BOLT/WRENCH CONTACT WITH LONG EXTENSION



F-7310

LANYARD ATTACHMENT OF SCREWDRIVER TO WRIST

Figure 5-21

The difficulty the subject had in making wrench to bolt contact, whether he was using small, large, open end, or adjustable wrenches leads to the assumption that the subject was not getting the feedback through the gloved hand that is associated with performance in ordinary work situations. This assumption was supported by the subject's attempts to compensate for the lack of appropriate feeback by performing all the wrenching tasks within his visual field (Figure *5-22).* When the subject could not see his work spot, he could not successfully remove a bolt or nut.

Within the observations made, during the maintenance tasks, it was concluded that the open-end wrenches were the most satisfactory (Figure 5-*23).* Generally, the larger the wrench, the better the performance. An exception is that during the maintenance tests, where good steady positioning of the subject could be obtained when using the foot or cage restraint, the T-socket and the ratchet wrench worked as well as any combination of wrenches tested.

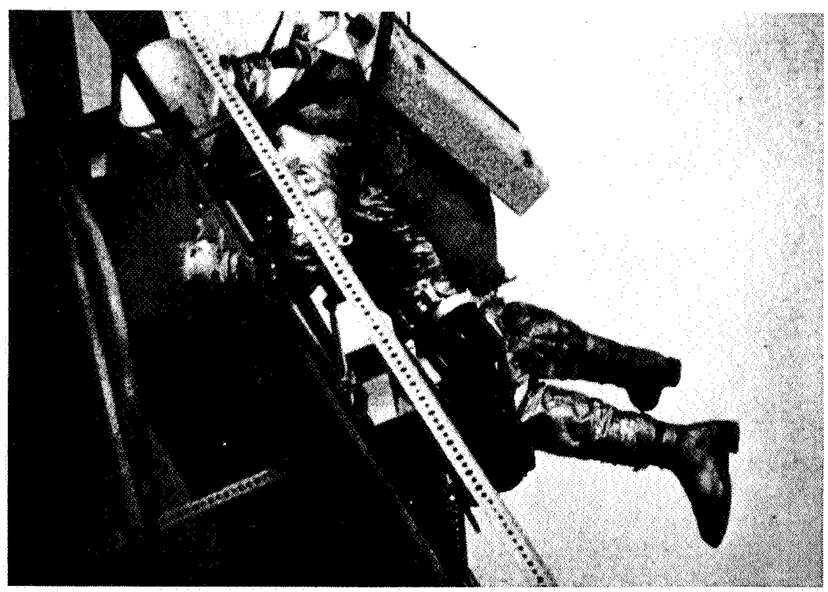
Screwdrivers

The most unsatisfactory of the common tools tested was the screwdriver. The push-away effect resulting from the use of the tool, and the necessity for constant control by the operator to keep the tool in contact with the slotted head of the crew makes the task impossible unless the subject is in a stabilized position (Figure *5-24).* In addition, position is very difficult to maintain because to operate the tool, the subject must push on it. This causes loss of position and requires subject repositioning to the work. The necessity to fit the tool's blade into the screw slot is undesirable and can, to a large degree, be eliminated by using something similar to an Allen-headed bolt instead. If such an innovation were used, the need of the screwdriver could largely be eliminated since a wrenching type of tool could be substituted.

A small screwdriver was used for many of the tests to evaluate the dexterity ability of the subject. One task required the removal and replacement of a small electrical switch, including the disconnection and reconnection of the electrical wires. The success of this task was principally dependent on the steadiness of the position of the subject during the work (Figure 5-25).

The slotted head fastener should be eliminated from the design requirement for "space" assembly and erection; if not, then modification of the screwdriver is mandatory for better interface with the state-of-the-art pressure suits. The subject, without exception, palmed the tool to operate it. Instead of holding the screwdriver in the normal manner, the end of the handle was placed in the palm of the hand, and the tool was turned by the thumb and forefinger. In this position, large torque forces could not be applied. If the handle was modified to a 3- or 4-in. diameter, then palming and exerting a larger torque would be possible. The subject commented that all the screwdrivers handles were too small.

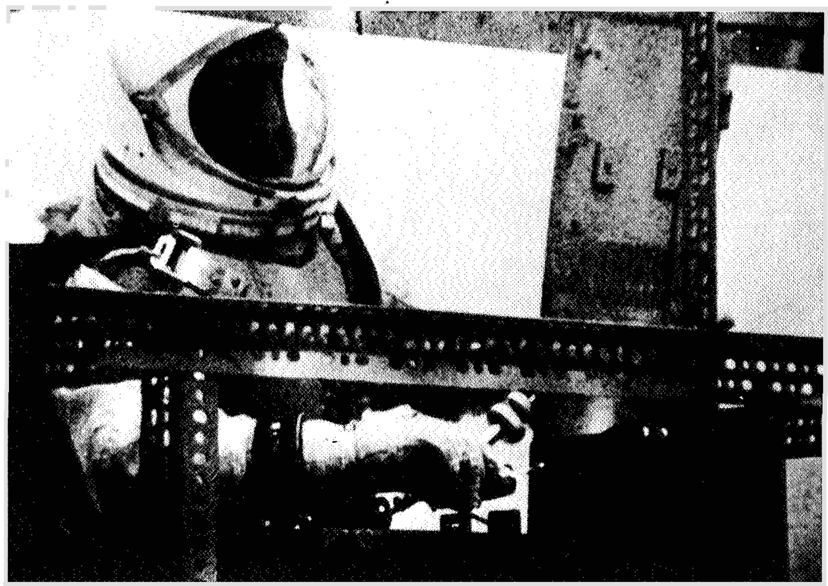
SUBJECT MOVING BACK TO SEE WRENCHING TASK



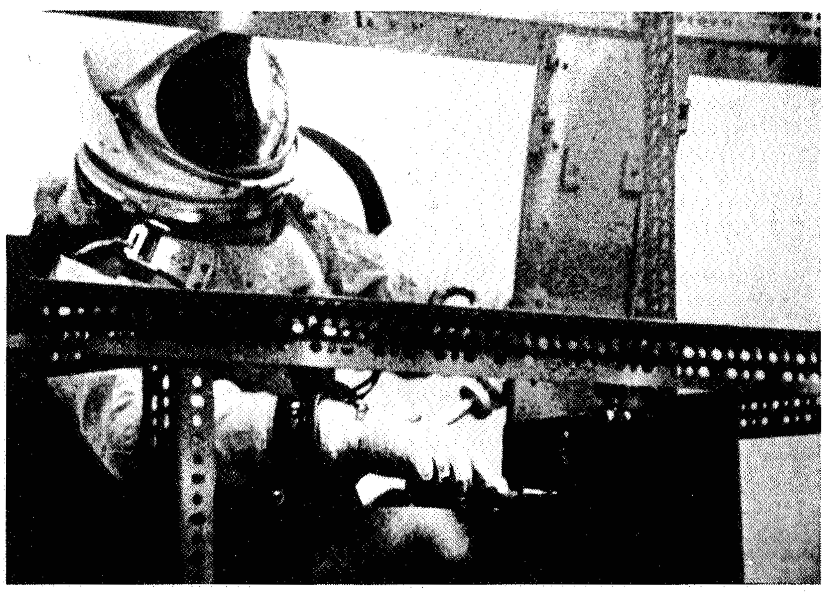
SUBJECT MOVING IN TO SEE WRENCHING TASK

F-7311

Figure 5-22



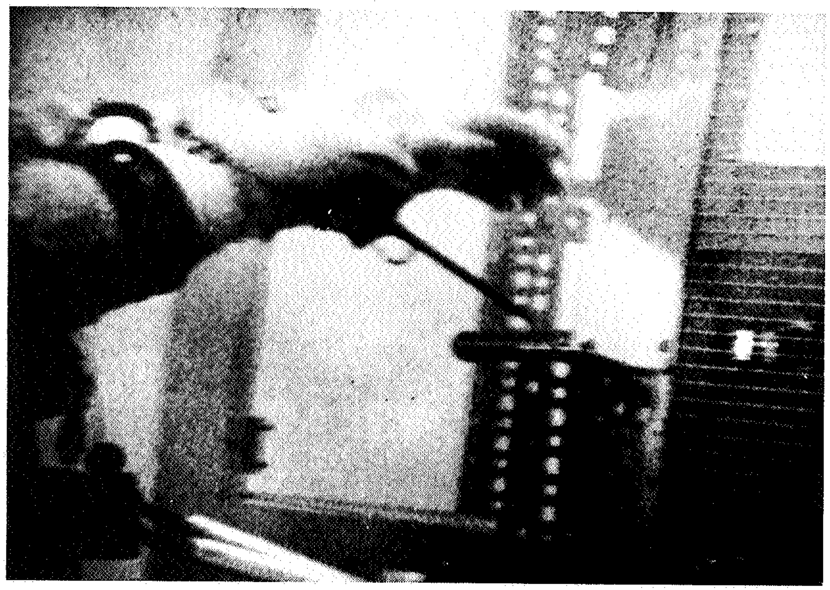
SUCCESSFUL PERFORMANCE OF AN OPEN END WRENCHING TASK: SEQUENCE 1



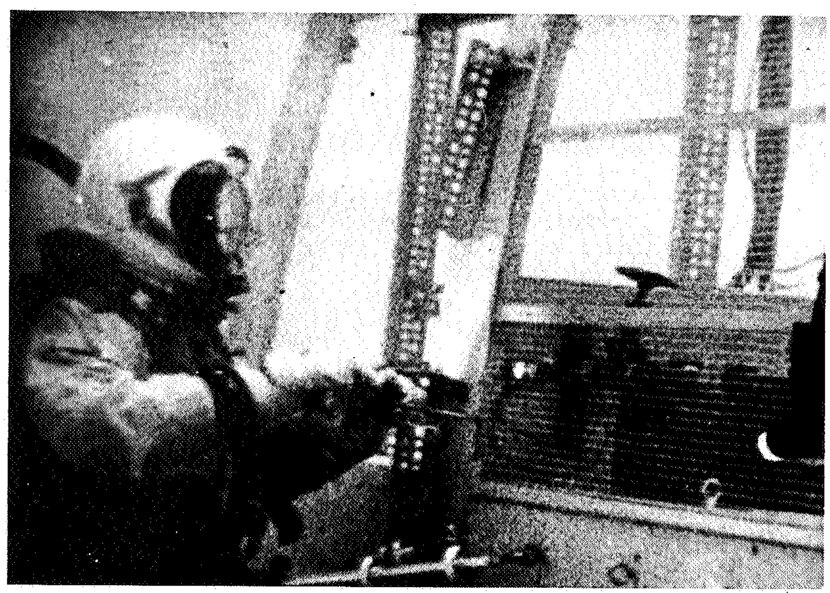
F-7312

SUCCESSFUL PERFORMANCE OF AN OPEN END WRENCHING TASK: SEQUENCE 2

Figure 5-23



"PUSH-OFF-EFFECT" BREAKING POSITION



F-7313

SUBJECT USING TWO HANDS TO GUIDE
SCREWDRIVER BLADE TO SCREW SLOT

Figure 5-24

F-7314

SUBJECT WITH LEG IN ACCESS OPENING TO GAIN STABILITY FOR PERFORMING A "FINE" TASK

Figure 5-25

The arm and wrist movements required to operate a screwdriver in a pressure suit are very difficult to make. The involved dynamics have not been isolated in this study, but all screwdriver use was accompanied by arm fatigue that required the subject to rest often and move the arm back and forth to prevent or remove muscle cramps. Following the tests in which the screwdriver was used, the subject's arm would be chafed from rubbing against the suit. It was concluded that the suit configuration was to a large part responsible for the difficulty of operating the screwdriver. Different suit configurations may eliminate this problem. Meanwhile, the screwdriver appears to be a very undesirable tool for EVA.

LOCOMOTION AIDS

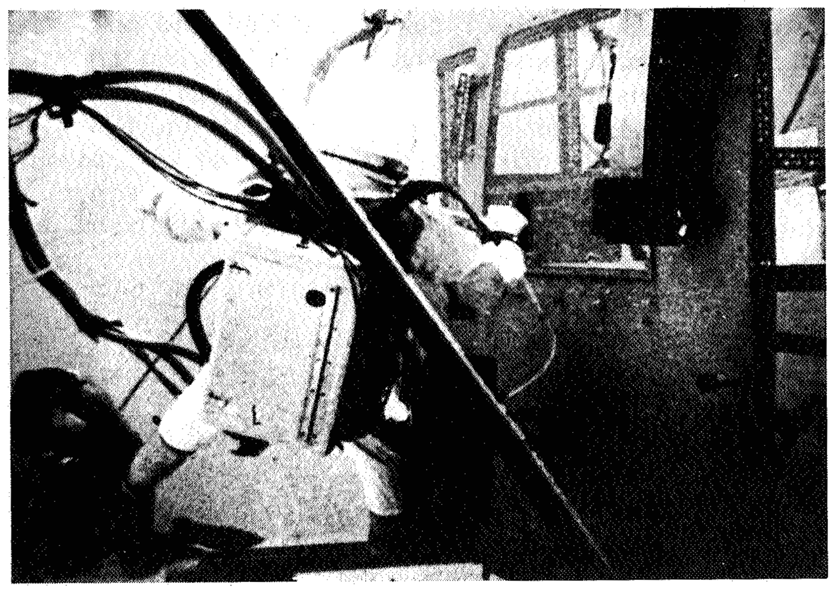
Five locomotion aids were used during the tests: (1) rope tether, (2) hand rail, (3) hand hold, (4) taut rope, and (5) rigid pole.

Rope Tether

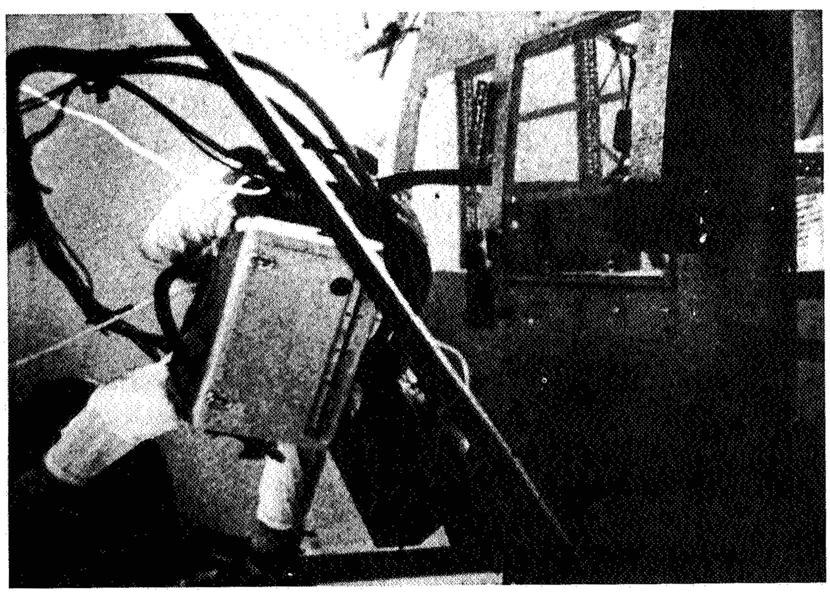
The selection of the five concepts to be tested was based on the assumption that the simplest manner of providing the astronaut with a means of holding on to an object attached to his vehicle would be the first types of locomotion devices used. The most elementary of these is the tope tether, which consists simply of attaching a rope to the vehicle and securing the other end to the subject. This locomotion aid is satisfactory for return only. Traversing to a work position must utilize some other means. As the subject gathered the rope to him to traverse, he would tumble and turn and soon be out of control (Figure 5-26). The damping effect of the water immersion simulation assisted the subject in maintaining control with this locomotion aid. During maintenance testing, however, the rope tether was found to be an unsatisfactory locomotion aid because of the time consumed by the subject trying to utilize it, and it was deleted from the tests.

Hand Rail

The hand rail consisted of a length of tubing attached at both ends and set approximately 6 in. out from the surface of the vehicle mockup. The subject used it in traversing from the hatch to the work station at the access opening (Figure 5-27). The motion or means of locomotion most often used is described as a crab-like movement. The subject would slide one hand forward, tighten his grip on the rail, and then bring the other hand up to it. His body would move parallel to the rail and in an upright position. A hand-over-hand movement with the body horizontal to the rail was seldom used.



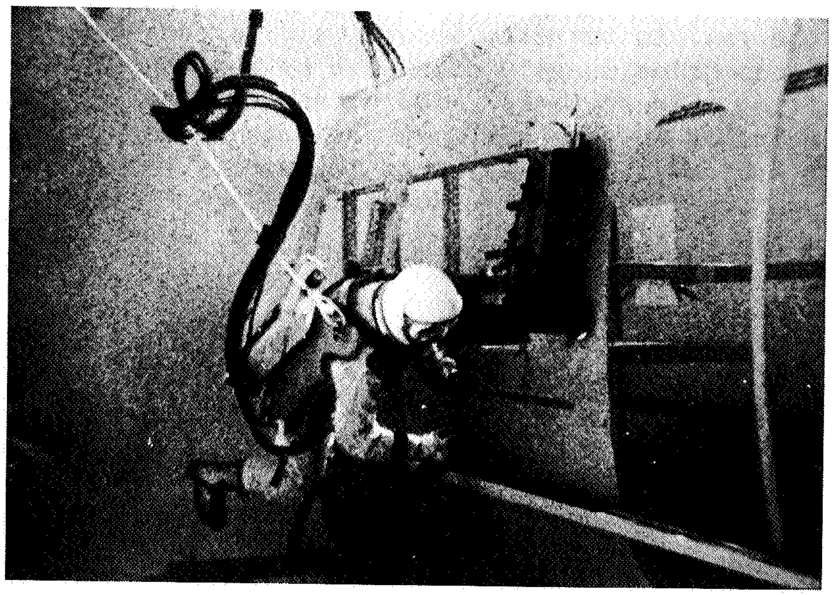
CONTROL PROBLEM WITH ROPE TETHER: SEQUENCE 1



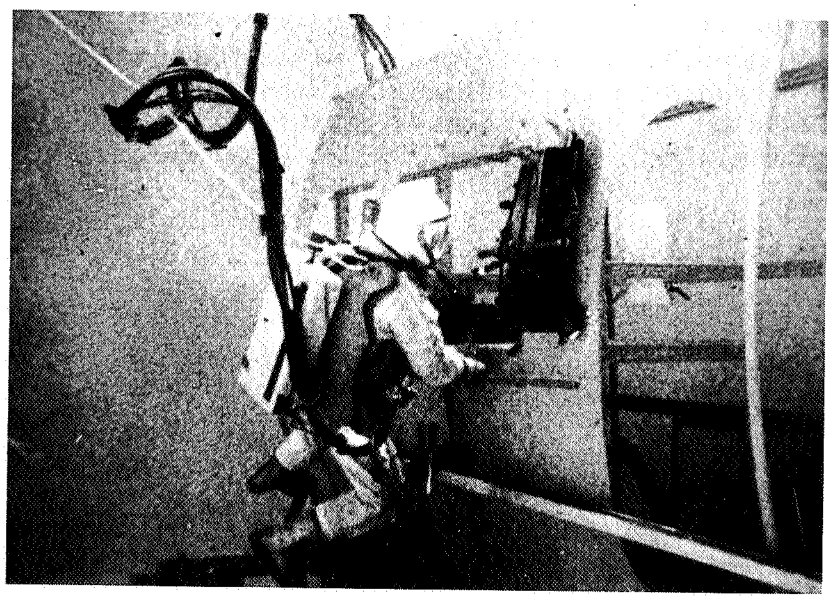
F-7315

CONTROL PROBLEM WITH ROPE TETHER: SEQUENCE 2

Figure 5-26



USE OF HANDRAIL TO TRAVERSE



USE OF HANDRAIL TO POSITION

F-7316

Figure 5-27

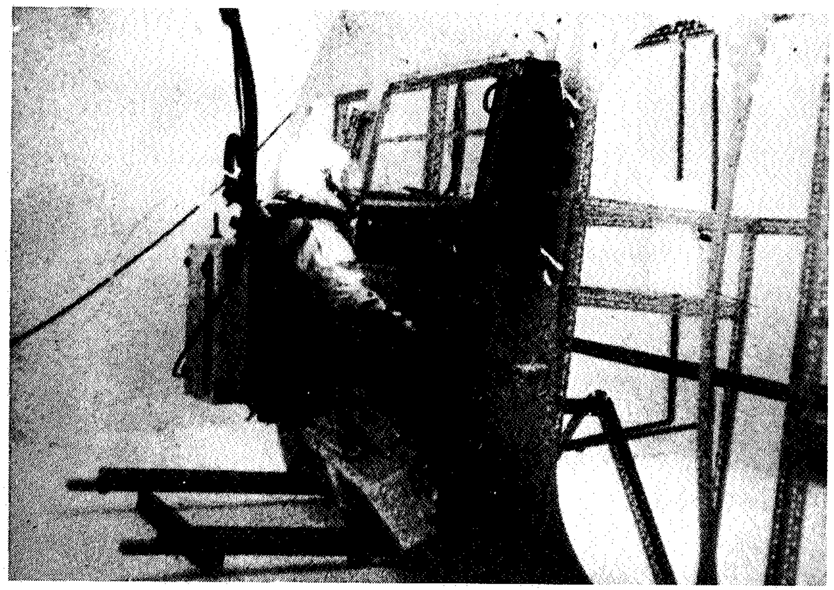
During the actual task performance sequences the subject would frequently use the rail to correct, secure, aid, or change his work position. This locomotion usually consisted of reaching out and grasping the rail and pulling (Figure 5-28). On occasions, the subject used the hand rail as a means of holding his work position by hooking a foot, knee, or arm behind or around it. It was noted throughout the tests that the subject took advantage of any protrusion available to secure his position by binding a limb in or on it in some manner. The hand rail was an acceptable locomotion aid configuration and worked as well as any other concept tested.

Hand Hold

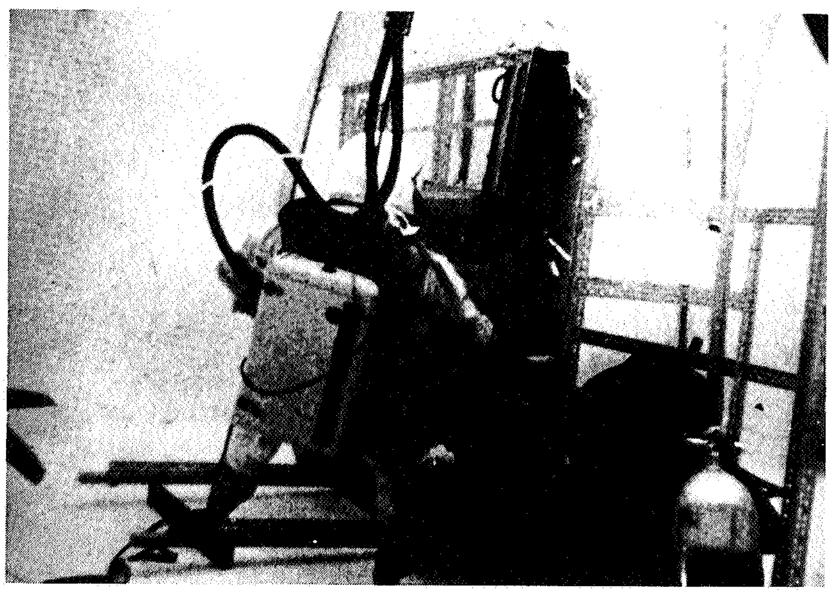
Two configurations of hand-hold locomotion aids were tested. The first consisted of a ladder with adjustable rungs so constructed that they could be set any desired distance apart. The other hand-hold configuration consisted of T-handles that could be set in the mockup's maintenance boom; these also could be adjusted to any desired distance apart (Figure 5-29).

The ladder configuration was used in both a vertical and horizontal plane (the orientation is in reference to the rungs). There was no observable difference in the functional aspect of the ladder as a locomotion aid associated with these two positions. The ladder was as satisfactory as the hand rail or the T-handles. If there exists a functional difference, it is associated with the cleaner lines of the ladder design, thereby presenting fewer obstacles that the many objects attached to the pressure suit can become caught upon and preventing the subject from moving along the locomotion aid. Changes in the distance between the rungs on the ladder from 12 to 16 in. did not appear to make an observable difference. The subject used the side rails on the ladder as hand holds as often as he did the rungs.

The T hand-hold configuration consisted of a 6-in. upright with a 12-in. cross member. The subject used it in the "crab" manner and in the hand-over-hand traverse method with the body horizontal to the boom. The hand-over-hand method appeared to be the fastest means of traversing. However, it was seldom used by the subject for distances of less than 10 ft. The "crab" motion was nearly always used for small traverses of under 10 ft. When the "crab" motion was used for longer traverses, the subject often had trouble keeping his body away from the locomotion aid, and hooked objects attached to the suit on the handles. Control of body position was harder to maintain over long traverses with the "crab" technique (Figures 5-30).



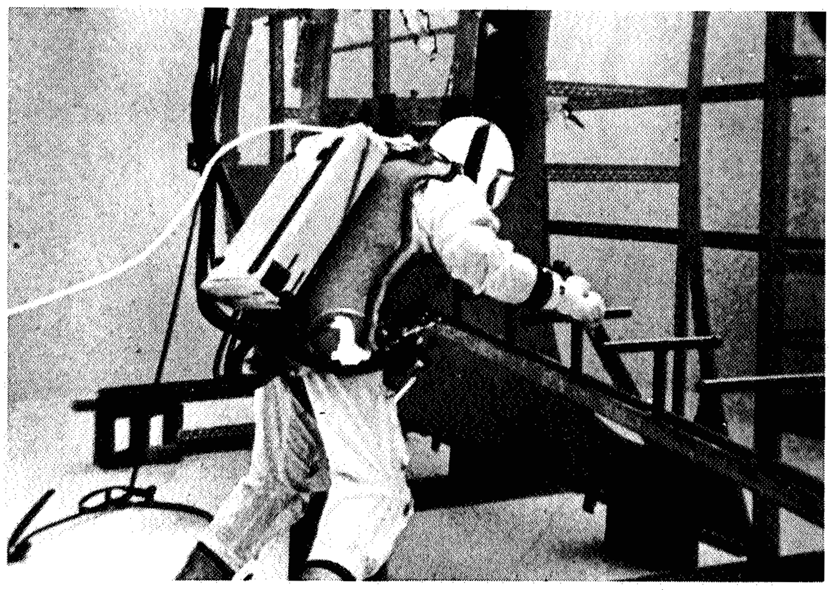
USE OF HANDRAIL TO POSITION



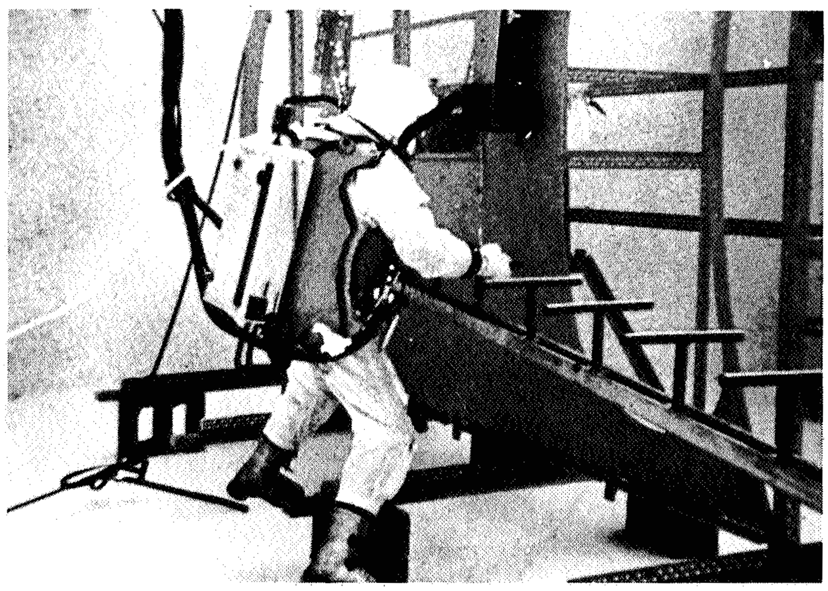
F-7317

USE OF HANDRAIL TO POSITION

Figure 5-28



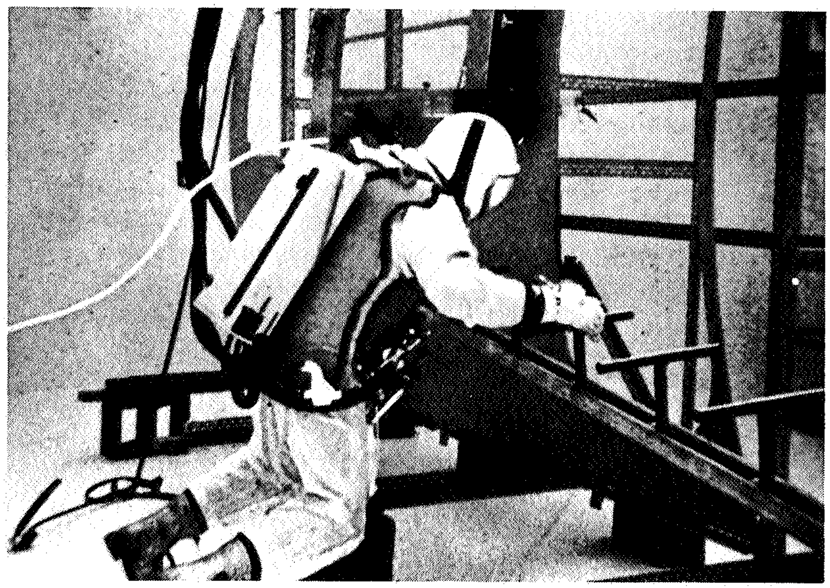
"CRAB" TRAVERSING WITH "T" HANDLES: SEQUENCE 1



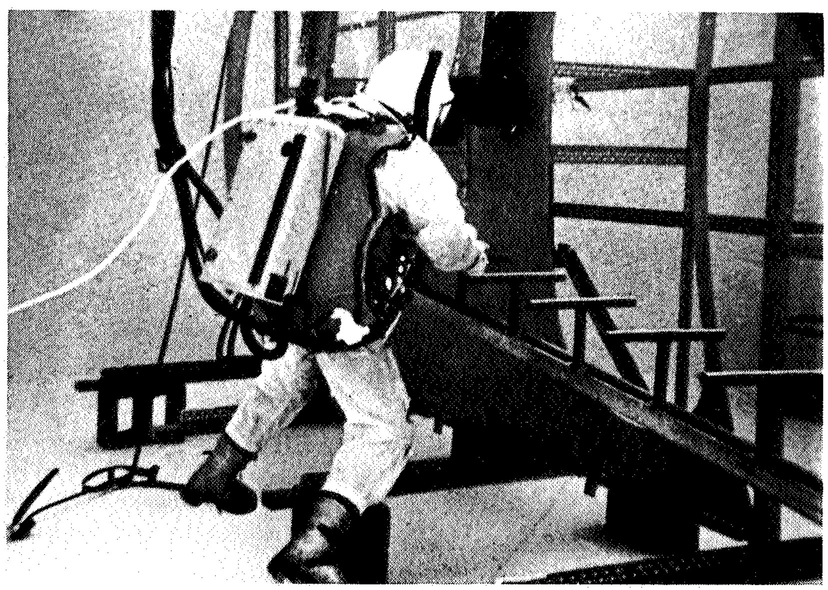
F-7318

"CRAB" TRAVERSING WITH "T" HANDLES: SEQUENCE 2

Figure 5-29



TORSO TIPPING DURING "CRAB" TRAVERSING
(CONTROL PROBLEM) : SEQUENCE 1



F-7319

TORSO TIPPING DURING "CRAB" TRAVERSING
(CONTROL PROBLEM) SEQUENCE 2

Figure **5-30**

Taut Rope

The taut rope locomotion aid consisted of a rope pulled taut and fixed at both ends; it was used in the same manner as the hand rail. The rail was removed from the front of the mockup and the rope substituted in the rail's place (Figure 5-31). The rope was used by the subject in the identical manner that the hand rail was used. It did not function as well as the rail did, since it had some play and "give" in it. In using the taut rope, the subject had to spend extra time making corrections for the movements brought about by the elastic aspect of the rope. The difference was not great, but did exist and is undesirable.

Rigid Pole

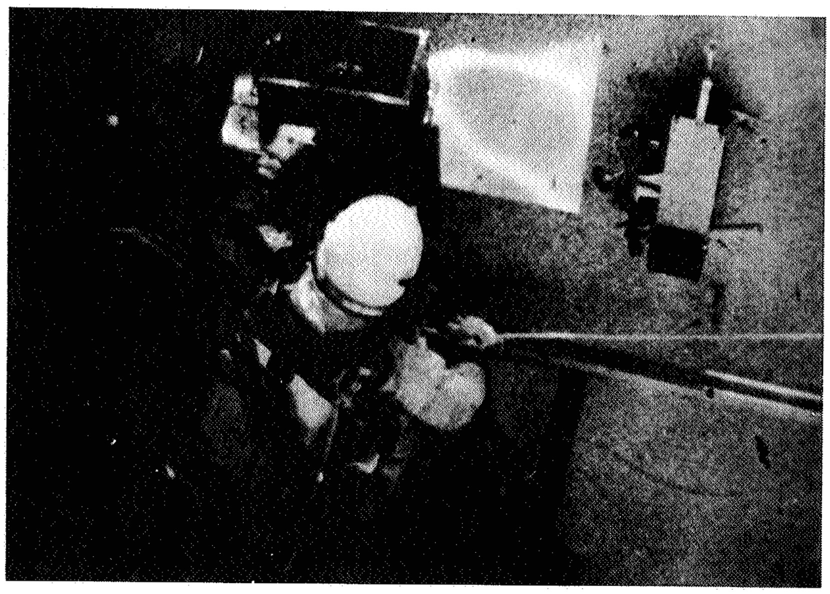
The rigid pole differed from the hand rail in that it was secured at one end only, leaving one end free and unattached (Figure 5-31). This configuration manifested some play and whip in the unattached end that caused the subject some loss of balance and control. For example, when the subject grasped the loose end of the pole, it would whip back and forth. The subject corrected this by simply holding on until the motion stopped. Then, generally in a head-first, hand-over-hand manner to keep the whipping motion to a minimum, he would pull himself along the pole (Figure 5-32). Some movement was observed in the pole that imparted rather a bouncing appearance, but the subject handled this very well, and it did not appear to interfere with his traversing.

The rigid pole locomotion configuration seems to be the most desirable one tested, not because it is more functional than the others, but because of its design simplicity and the flexibility it provides for extending out or away from the mother vehicle.

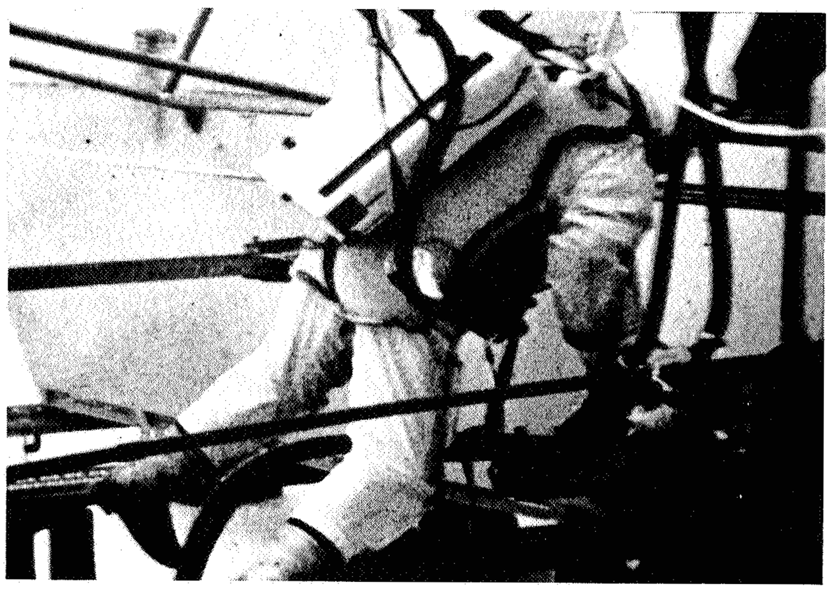
Fasteners

A review of a variety of fastener catalogs revealed no specific fastener concept that would meet the requirements for a universal fastener to be used for space assembly. Actually, from the point of view of the tasks to be performed during EVA, it appears that the selection of fasteners will be based on practically the same selection procedure as that used for any fastening problem. Added to these procedures will be the additional requirement imposed by the astronauts' pressurized gloves and the difficulty of applying torques in a weightless conditon. Basically, however, the selection of the fastener will depend on the requirements for strength, size, wear, heat exposure, electrical conductivity, and weight.

Although there are over 500,000 standard items which are identifiable by name, type, size, and material listed in the standards document, most of these are variations of the bolt and nut design. The majority of the special fasteners that deviated from the nut and bolt design are either special designs for specific purposes or variation of the drive-pin concept. The review of the fastener catalogs revealed no fasteners that could meet



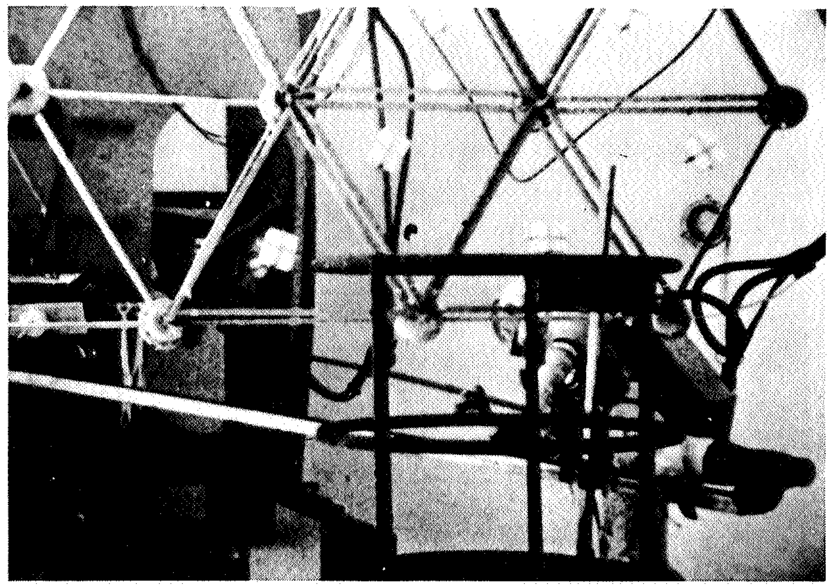
SUBJECT USING TAUT ROPE ON SPACECRAFT MOCKUP



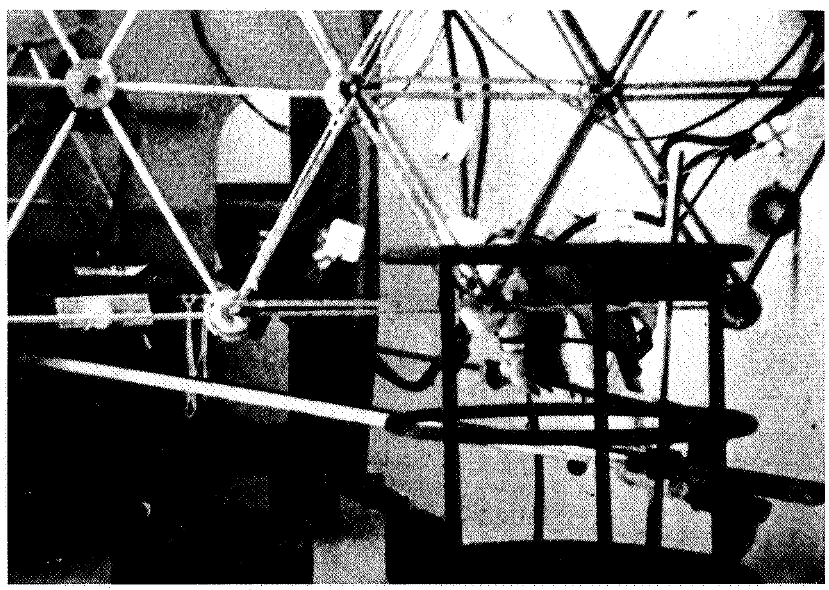
F-7320

RIGID POLE LOCOMOTION AID EXTENDING
AWAY FROM SPACECRAFT MOCKUP

Figure **5-31**



HEAD FIRST TRAVERSING USING RIGID POLE
LOCOMOTION AID: SEQUENCE 1



F-7321

HEAD FIRST TRAVERSING USING RIGID POLE
LOCOMOTION AID: SEQUENCE 2

Figure **5-32**

the universal application illustrated by the "expando-pin." This fastener appeared to fit the in-space erection and assembly requirement better than any other fastener. However, attempts to use the expando pin during the early phases of testing proved that their limited application was not appropriate for the fastening tasks of the EVA study.

The fasteners tested were a variety of types, rather than a representative sampling. They were arrived at as a compromise to illustrate the differences in fasteners from which specific selections could be made and to allow testing of off-the-shelf wrenches. The detailed fastener review did not reveal any specific new fastener concepts that would alleviate the fastener problem but, instead, pointed out that a design problem may exist in the EVA fastener area.

Three types of bolt heads were tested: external wrenching, internal wrenching, and slotted heads. These bolts were furnished in three sizes and referred to during the tests as large, medium, and small. The use of the three bolt sizes set the framework within which the observational judgments were made. These are identified and described in Table 2-2.

Small bolts were dropped, misaligned, time consuming, harder to remove, and resulted in more task failures than the large bolts in all test modes. The large bolts also had these same negative aspects associated with them, but were mishandled less frequently. Task performance success was better with the large bolts.

The internal wrenching heads were the most desirable, and the slotted head bolts were the least desirable. It was concluded that the the slotted head bolts should be eliminated from EVA whenever possible because of the difficulty encountered by the subject using the screwdriver. The advantages of the internal wrenching head are the increased ability to see and feel wrench contact with the bolt and the resulting improved efficiency in the turning of the bolt. No conclusion can currently be made as to whether a medium-sized internal wrenching bolt is more or less desirable than a large external wrenching bolt.

The subjects repeatedly had difficulties with all three types of small bolts that were handled with the pressurized gloves. It appeared that when the subject was working with small bolts, he had difficulty'knowing whether he had it in his hand or not unless he could actually see the bolt. Taking the bolt out of its position with the fingers and placing it in a container or holder proved to be an awkward and difficult task. The same tasks were performed better in every way with the large bolts.

Through all the maintenance tests the subject commented that the small bolts were impossible to handle. The subject had trouble wrenching all three small bolts because he could not tell by "feel" of the wrenches whether or not they had made a good connection on the bolt. The lack of feedback from the wrench had to be compensated for by the subject seeing the bolt-wrench connection during the wrenching tasks.

LARGE MODULE ERECTION AND ASSEMBLY

During the numerous tests conducted in the maintenance study, there was a gradual development of a "test" orientation by the subject that appeared to manifest itself as an independence, and certainly about the best means of performing the tests. The opinion of the human engineering observer is that the subject believed the tasks he performed in the maintenance test were easier to perform because of his improvement of the task sequences, and the overall improvement of the test structure as he improvised changes in it. The observer is inclined to discredit this since it is believed that the hardware configurations that were changed from one test situation to the next imposed more variation in the test situation than was observable to the subject. A secondary point is that the learning the subject was experiencing was apparently not obvious to him, and when he utilized these newly acquired techniques to improve his performance, he was attributing the improved "success" to his alteration of the procedures.

Although procedures were developed for the large module assembly and erection test, no insistence was made by the test conductor or the human engineering observer that these procedures be followed without deviation. Instead, it was felt advisable to present the procedures to the subject in the light of guidelines. The subject was instructed that, "the procedures represent a way in which we think the task could be performed. Since they have not been developed by actual tests, however, there is no certainty that the procedures are the best way to perform the task. You are doing the work and are in a better position to tell which step-by-step procedure for the individual task-elements must be done and the manner and sequence in which to do them." Thus, the subject was allowed to perform the work in the manner he believed to be the best.

This compromise was considered to be a mistake, and the notes taken by the human engineering observer, the analysis of the films of the tests, and comments and observations of the other team members support his conclusion. The tests were fraught with human error, so much so that frequently it was impossible to separate the judgment error of the subject from the hardware inadequacies. However, much was learned from the tests: insights for further studies were noted, natural positional attempts were repeated over and over and noted, and attempts by the subject to overcome the negative aspects of the pressure suit were quite obvious and were recorded. The latter is very evident in the film analysis. The outstanding observation is very simply that the procedure used in these large module tests--the subject devising his own sequence--is desirable.

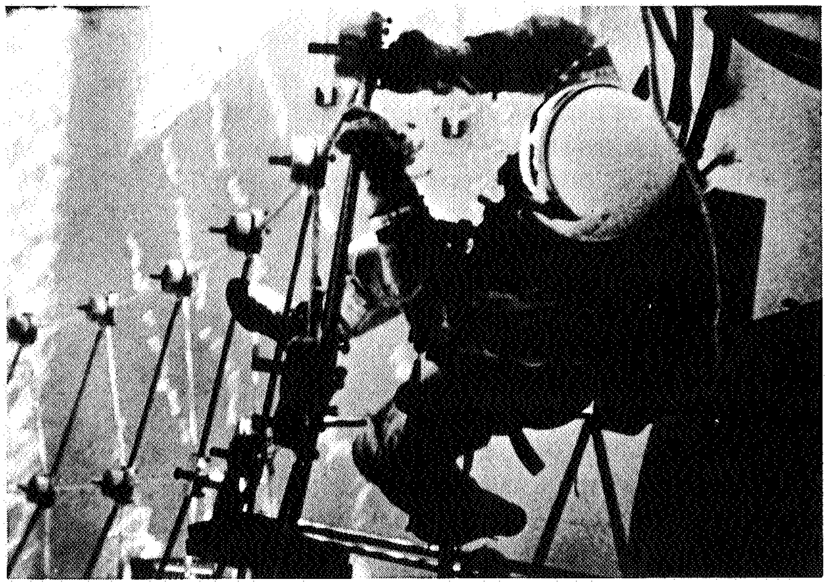
Putting the observation positively as an EVA guideline, "All EVA tasks of erection and assembly of large modules require step-by-step procedures developed by water immersion simulation techniques using real hardware to prove the concept, develop the procedures, and provide the training necessary to assure the success of the erection in space." This observation was also made during the maintenance test, but its most positive reinforcement came during the four large module tests.

Antenna

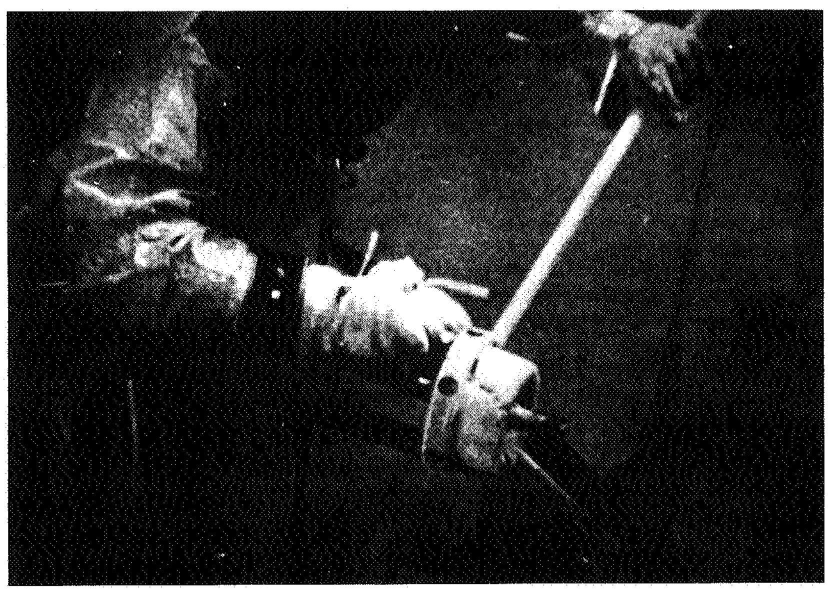
The use of the hardware for the subject to place his feet upon during the test of the antenna erection, although available, was not as functional for this task as during the maintenance tests, where the work spot was much more localized. Part of the consequences of the mobility required to get to the many work stations on the antenna was that the subject performed a large degree of the work of connecting the joints and beams in a "one-handed" manner. This task was in reality a two-handed task (Figure *5-33)*. The subject developed and continued to develop special adaptive techniques to perform the two-handed task-element with one hand (Figure *5-34)*. An analysis of these innovations requires the use of motion picture films where the same task-element can be looked at again and again and, if necessary, at reduced speed. Such techniques are true work improvement innovations. They are the type of behavioral insights discovered in practice and not the type that are taught, since so much of the behavior depends on such subtle aspects as the dexterity of the subject, his athletic ability, the length of neutral buoyancy exposure, and even pressure suit fit. Two-handed task-elements that are performed in this tricky and subtle way point out the innovations the subject came up with to perform the work when the standard lineman's position or variations thereof were not available to him.

The one-hand, two-hand, hold-on work was assisted by foot contact whenever the subject could obtain it (Figure *5-34)*. Such contact was almost always necessary in order to apply forces. For example, the beams would frequently bind as they were placed in the connecting hole of the fastener, and the subject would have to exert extra force, which required getting a position with an additional leverage advantage over that required when the joint did not bind. The foot used as a contact point was the most frequent approach used to solve this problem for additional leverage. When the foot was used to gain stability, the positioning was considered a two point position. It was noted that the further apart these positioning points of contact were, the more effective they seemed to be in providing the subject with the stability required. It was also noted that in the early maintenance tests, the feet entered into the positioning and stability very little, but were used more and more as the subject gained experience in the neutral buoyancy simulation.

The antenna configuration lent itself to the use of the legs and feet for support. For example, the antenna boom was used as a locomotion aid, a type of cage restraint, a steadying device, and a place to hook a foot or knee. The antenna dish was used in the same manner but had the disadvantages of being considerably more flexible, less stable, and occasionally coming apart if the subject allowed too much force to be transferred to it. This tended to keep the subject "off' the antenna dish, and he would work as much as possible from the antenna boom or from the maintenance boom to erect the antenna dish.



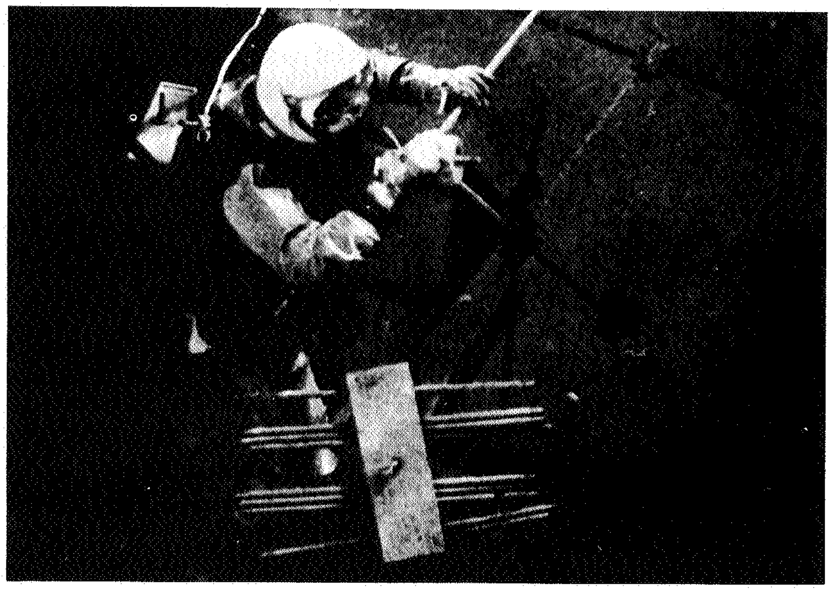
USING FOOT TO KEEP JOINT/BEAM CONNECTION
TIGHT WHILE TIGHTENING THUMBSCREW



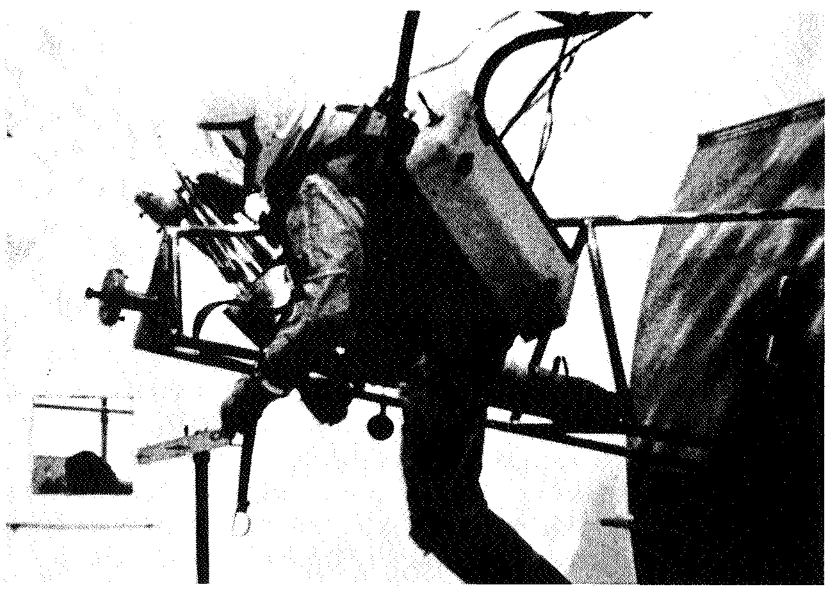
F-7322

USING HANDS TO KEEP JOINT/BEAM CONNECTION
TIGHT WHILE TIGHTENING THUMBSCREW

Figure 5-33



SUBJECT HOLDING HIMSELF IN POSITION
AND WORKING AT THE SAME TIME



F-7323

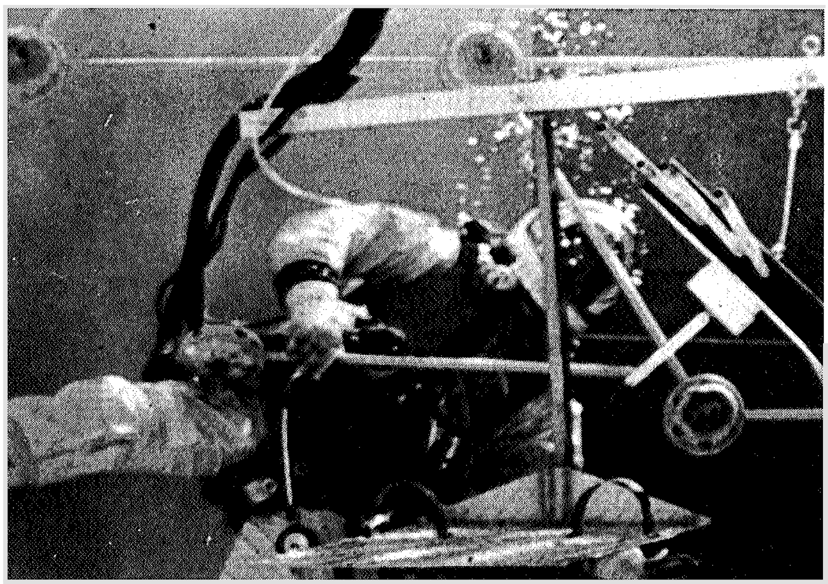
SUBJECT USING ONE FOOT ON ANTENNA BOOM FOR STABILITY
SUCH THAT BOTH HANDS ARE FREE TO PERFORM WORK

Figure *5-34*

The feet were used to get the second contact point for good positioning and stability in the assembly work. This was not noted or recorded during the observation of the task at the time the tests were being conducted, but came to light during the film analysis. The subject would use his foot to hook under one of the joint/beam combinations to steady it and hold it in place while he worked on its counterpart. This position would give him stability to hold the joint/beam steady and keep it from coming apart. At the same time, he was allowed to work with two hands on the connection. This is one more example of the fine and subtle types of work improvement that took place during the antenna assembly.

The subject used the end of the antenna dish as a positioning station for connecting the joints and beams (Figure 5-35). Several work advantages existed for the subjected in this position: the advantage of transferring the forces resulting from the subject's work along the longitudinal axis of the antenna dish, thus reducing the amount of "play" imparted to the structure, the ability to use the waist strap restraint by puching back against it with the hands, the ability to move up and down at the end of the antenna without changing the length of the strap restraint or connecting or disconnecting it, and the advantage of being able to approach the thumb screws of the joints with the side approach of the arm. The latter seems to be a natural approach to work, and the subject has frequently been observed favoring this approach as opposed to a direct frontal movement of the arm. Positions assumed while using the cage and foot restraints were, however, more functional than the position at the end of the antenna.

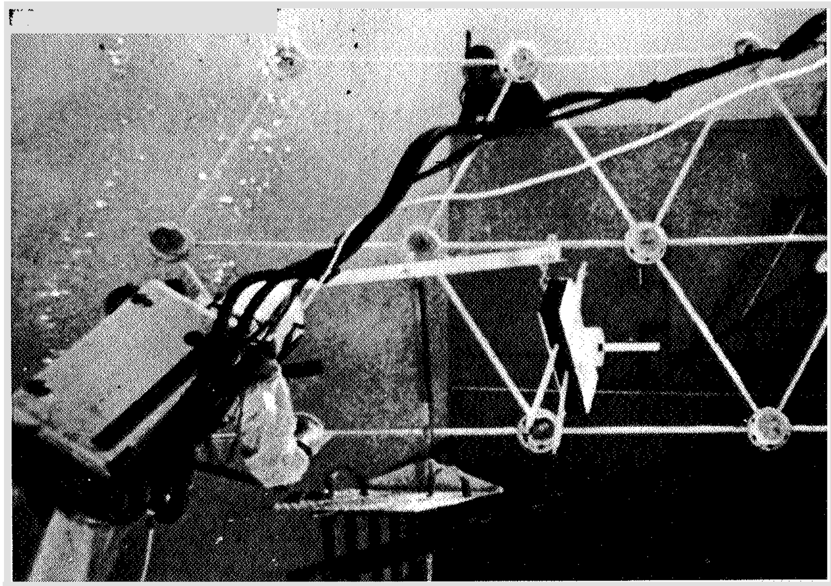
Permitting the subject the freedom to select the sequence of work to assemble the antenna resulted in a great loss of time because the subject studied the antenna to find out what step would logically follow. The logic was often in error and the subject had to rework some joint and beam connections. When the configuration of the antenna dish was near completion, the subject found that he had left out three of the beams and one end of the antenna had to be disassembled and reassembled with the missing beams included in the structure (Figure 5-36). It was concluded that the common sense workaday approach was inefficient in that an error of erection had been made that was costly in time and in the strength of the antenna structure. When the beams were riot firmly set in place in a step-by-step development, the antenna became "sloppy" and would come apart due to stresses from movements of the subject. The subject stated that he could not assemble the antenna dish from the rear, yet the film shows the subject working from the rear, from the front, from the end, on his side, and even head down (Figures 5-36 and 5-37). Whether or not these positions are of equal performance level is in this case unimportant. What is important is that the prejudgment of the task difficulty and the capability of the subject to perform the tasks were not necessarily valid. This resulted in frequent mistakes that could have been avoided.



F-7324

SUBJECT WORKING AT ONE END OF THE ANTENNA DISH

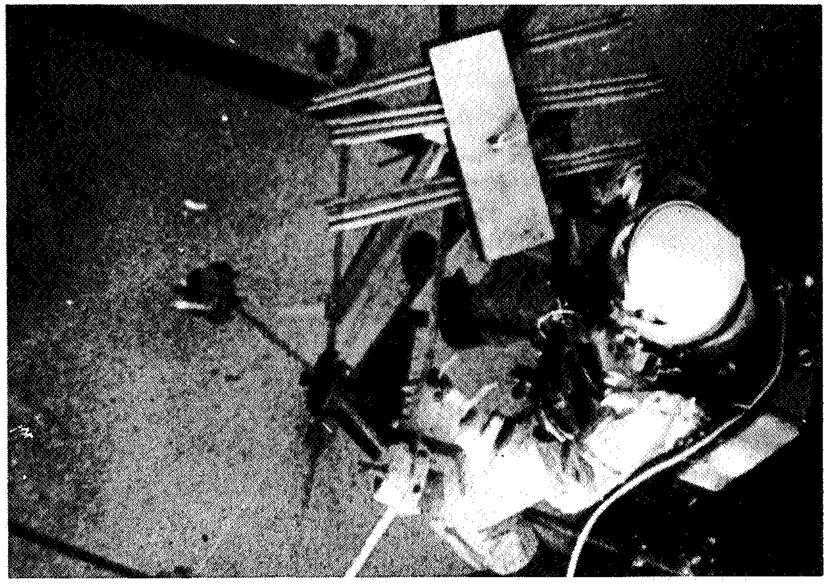
Figure **5-35**



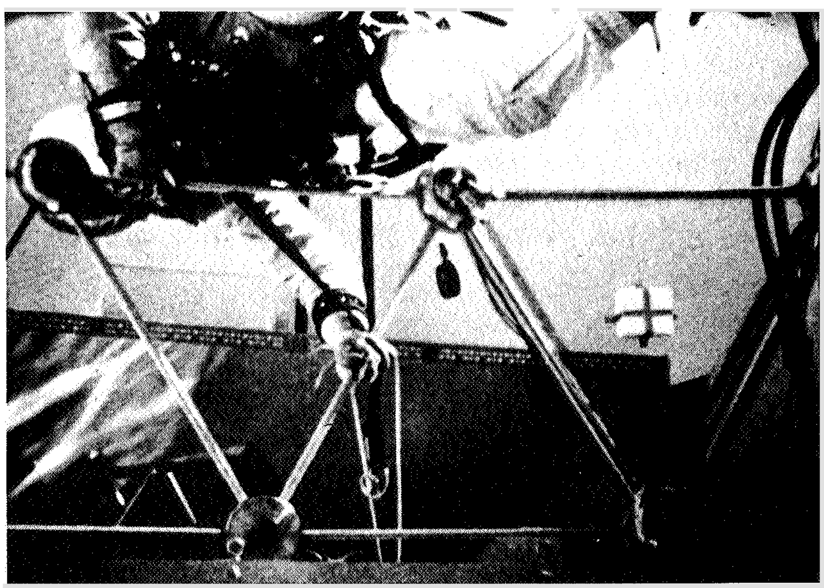
NTENNA ASSEMBLED WITHOUT SOME OF THE REQU RI

SUBJECT ASSEMBLING ANTENNA FROM THE BACK SIDE F-7325

Figure 5-36



SUBJECT ASSEMBLING ANTENNA FROM THE FRONT SIDE



F-7326

SUBJECT TRAVERSING OVER TOP OF ANTENNA TO GET TO BACK SIDE

Figure 5-37

The use of the maintenance boom with a cross bar attached for the connecting of the Gemini XII type of strap restraints was not as successful as that of the cage and foot restraint. The boom with only the cross bar did not provide a surface area large enough for the foot positioning necessary in the assumption of the lineman's position. Also, the length of the maintenance boom extending out to the face of the antenna provided a considerable amount of give and flexing. This caused more difficulty in assuming and maintaining a good position when using the cross bar than when using the cage and foot restraints (Figure 5-38). The exception to this was when some of the lower parts of the antenna had to be reached. The subject had difficulty getting to them to perform the work. On occasions, it was necessary to leave the cage or the foot restraint to get to these lower work points (Figure *5-38).* As a rule, the subject found a way of getting to the lower connections and still utilize the restraint in some manner to hold his feet or legs and provide the essential second point of contact that gave the necessary stability to perform the task.

Traversing

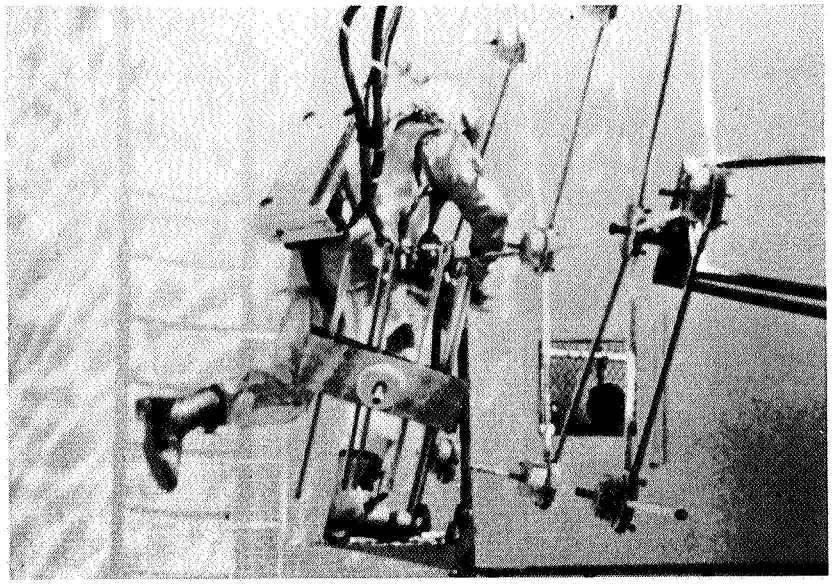
When the subject moved any distances in excess of 6 ft using the antenna face as his locmotion aid, he traversed nearly as well as he did when traversing like distances using the rigid type of locomotion aids. It seems reasonable to assume that special locomotion aids on open beam-type structures will not be required in EVA. The maintenance boom, the antenna boom, and the antenna face were all effective locomotion aids (Figure *5-39).* The desirable characteristic for locomotion aids appears to be rigidity and lack of protrusions for catching the astronaut's pressure suit and the many objects attached to it. During traversing, the subject was frequently stopped by any protrusion that could catch the suit. This is a very serious problem, and the nature of it is such that as the total system develops, the problem tends to increase. Notes taken from analysis of the films of the antenna assembly tests are included as a brief summary of the important observations previously stated.

Notes from the Antenna Film

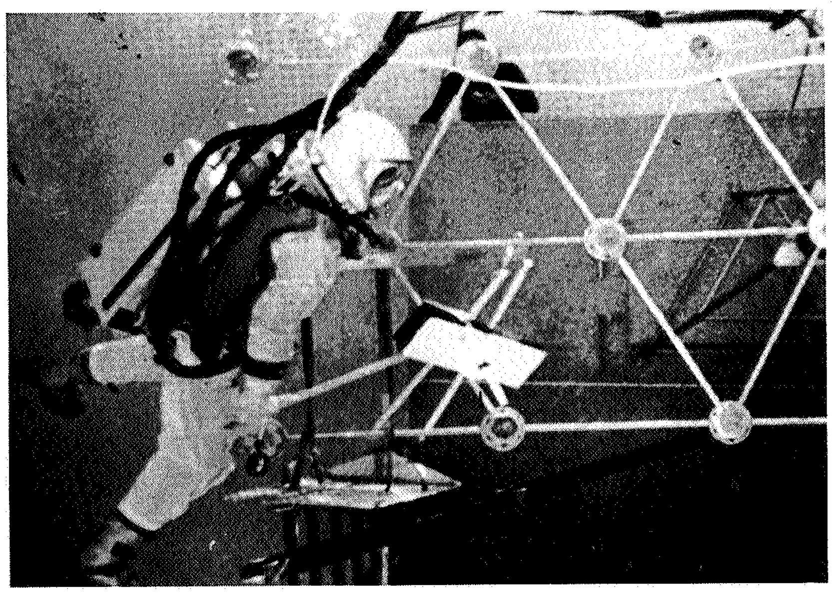
a. Considerable amount of time was wasted by the subject trying to figure out how to put the antenna together.

b. The film does not show any difference in the ability of the subject to operate the thumb screws from either the front or the back of the antenna.

c. The work done on the antenna dish without the foot or the cage restraint was done (to a large part) by using various one- and two-hand techniques. The trick is to do work and hold on at the same time.



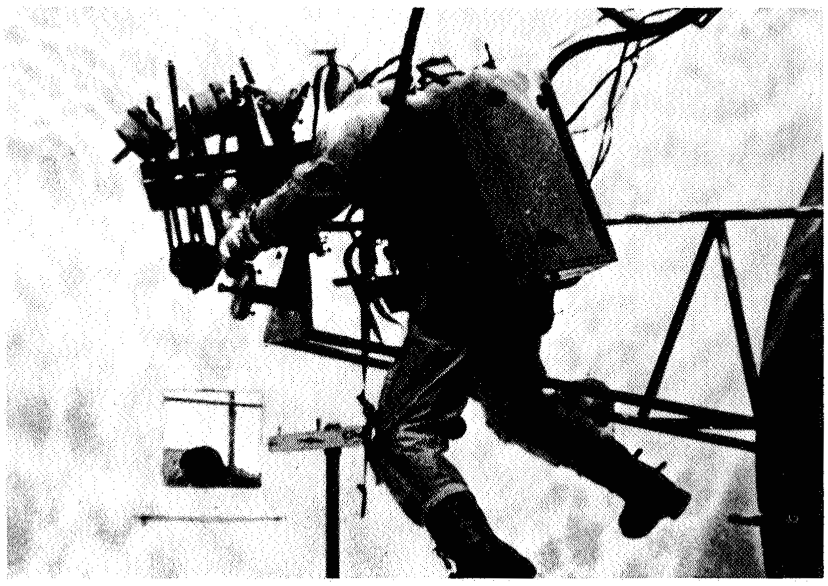
"GOOD" WORK POSITION USING STRAP-FOOT RESTRAINT



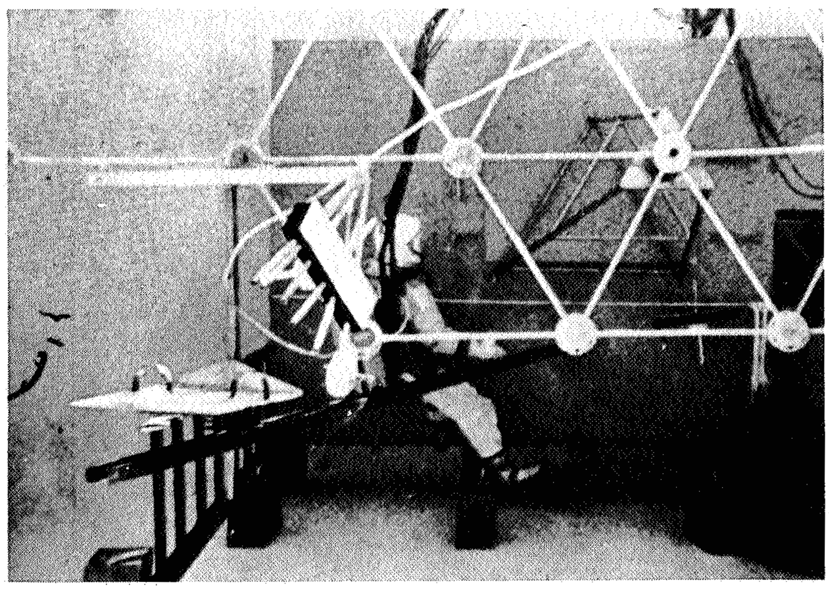
F-7327

SUBJECT LEAVING STRAP-FOOT RESTRAINT
TO WORK ON LOWER SECTION OF ANTENNA

Figure 5-38



SUBJECT USING ONE HAND ANTENNA BOOM TO TRAVERSE



F-7328

SUBJECT USING ONE HAND ON MAINTENANCE BOOM TO TRAVERSE

Figure 5-39

d. When the subject worked from the front of the antenna, or from the end of it, he seemed to use the natural motion of the suit's arm to come in sideways to the thumb screw.

e. New connecting snaps are needed on the strap restraints in any further testing. The straps should be stiffer.

f. The subject discovered some rather unique uses of his foot to help hold the antenna together while he worked on it. The foot in effect became a "third hand."

g. The subject climbing about the antenna and the antenna boom by using his hands was effective traversing.

h. Pulling on an attachment at the waist is not a very stable locomotion means.

i. Connections for good restraints on the equipment being worked on is mandatory for good EVA performance.

FOLDING PANELS (ANTENNA FACE)

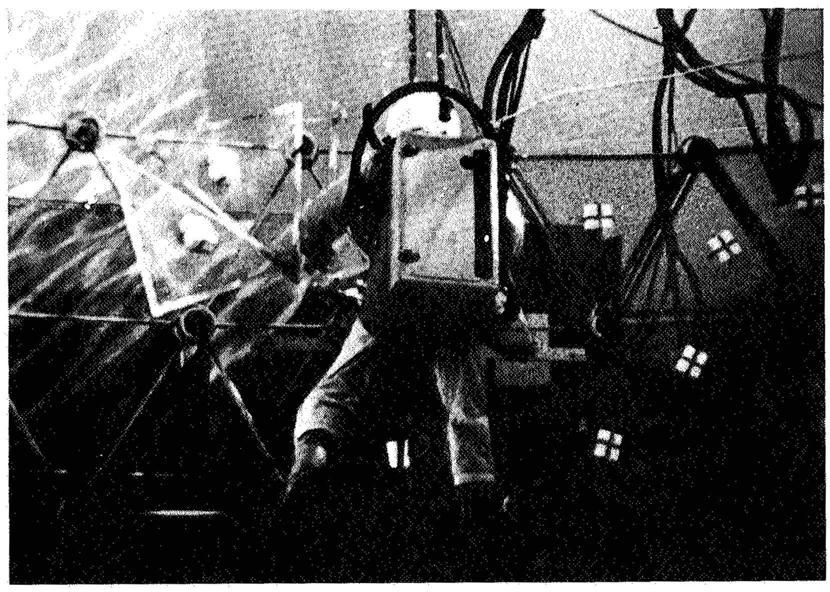
This test was an outstanding example of the necessity of preestablished step-by-ste- work procedures being used for EVA simulation. It is a must for EVA simulation, for EVA training, and consequently for transfer to EVA in space.

Protruding from each joint of the antenna face was a l-in. wood dowel with an exposed length of approximately 2 in. These dowels were the connecting points for the panels. The connection consisted of placing an elastic cord over this dowel so that the tension would hold the panel in place (Figure *5-40).* The panel was triangular and the same shape as the antenna's triangular configuration. At each corner of the panel was an elastic cord to be slipped over the dowel. Four panels were folded together in an accordion fashion. The surface of the panel to be placed on the exposed front of the antenna dish was identified by a small block of plastic foam placed there to make the panel neutrally buoyant. It was believed that in this manner the subject could readily distinguish which surface of the panels to place on the antenna face. The prepared procedures depicted the task-elements of the assembly, including two drawings showing the panels in place. This procedure, as defined by the task sequence, was then tested at one g and found workable. It was then tested in water immersion by scuba divers and found workable.

The established procedures were not followed by the test subject. The tests for the folding panels were performed on two consecutive days, and there appeared to be little or no improvement in the performance level of the subject. The human engineering observer for these tests believes that the subject did not make an adequate attempt to learn or understand the simple task procedures before or during the tests. The fact that a

SUBJECT PLACING PANELS ON ANTENNA FACE F-7329

Figure 5-40



PANELS FLOATING FREE AT ONE END, UNCONTROLLED F-7330

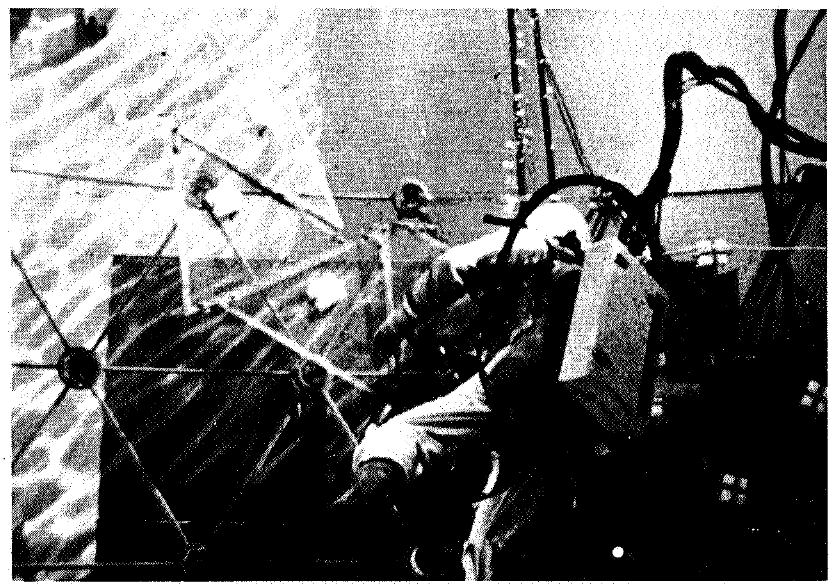
Figure 5-41

scuba diver could swim over to the antenna during the test, and in a matter of seconds position the folding panels for attachment to the antenna face, did not apparently influence the subject's motivational set for learning or improving his performance in the task.

The use of the elastic cord as a hinging mechanism as well as connecting points for attaching the panels to the face of the antenna proved unsatisfactory. The hinging should be metal, allowing movement in two directions only. Alignment would then be simplified by the panels tendency to center themselves after the first connection has been made. The fastener problem associated with the panel application to the antenna did not lend itself to a simple solution. As the connections between the panels existed for the test, they were far too flexible, and the freedom they possessed to move in any direction complicated the assembly task considerably. The practice of the subject to "throw" the package out away from himself while holding on to one end of a panel and thus be able to see and examine it was a complication that was unnecessary and compounded the problem of panel placement for attachment (Figure 5-41).

Further testing is obviously required of larger panels attached by hinge mechanisms, and it would be desirable if a locking mechanism was included to place the panels at the desired angle and eliminate the tendency of such structures to collapse. Two-, three-, and four-sided panel structures should be used. The tests showed, however, that small panels in packages of four could be attached, manipulated, and successfully used in the water immersion simulation technique. It also reinforced the earlier observations that fasteners for EVA have every indication of being a major problem area.

There were many unrestrained work attempts in this test. Since the restraints provided were identical to those used for the assembly of the antenna, this difference is attributed to the nature of the work being performed or, to put it another way, caused by the change in the hardware being manipluated by the subject. One explanation is that the four panels as handled by the subject provided a much larger surafce area than had prior tasks and the coupling used made it very difficult to manage. The subject, in attempting to manipulate the panels, was "required" to use more mobility within the task sequence of connecting the four panels then in prior tasks. To get the required mobility, he would often "break" free of the secondary contact point, which was usually at the foot (Figure 7A-42). The foot was frequently used as a pivoting point, allowing the upper torso to swing in a rather large arc. This technique worked best from the cage restraint. The reason for this seemed to be that the pivoting point of the foot could be moved about within the cage. That is, the foot could be hooked or held in place at several different levels and at different depths within the cage in reference to the pivoting point of the body's arc. This gave the "work" arc greater range and flexibility. The range of the work arc could not be obtained as well with the foot restraint since there were only the two stirrups for connecting points from which the foot could be used as a pivot point. It was difficult for the subject to maintain this position because much moving about was required to get the panels positioned for connecting. At such time, the subject would often "float" free, having no connection other than his waist strap while seeking a second connection



F-7331

SUBJECT "FALLING" FROM POSITION WITH PANELS

Figure 5-42

with his feet or one of his hands, When this latter condition existed, very little assembly work was accomplished by the subject. The majority of this free-floating time was spent seeking some kind of secondary contact point to provide positional stability. Other than this deviation, the positioning and stability dynamics of the work position did not alter observably from those found and discussed for the tests conducted up to this time. For example, the variations of the lineman's position were used with both the cage and foot restraint. The controlled falling that the subject had used in the cage was again observed, as well as the spread-leg type of position and, of course, the subject's holding on with one hand while working with the other.

The only tool required for this test was the use of the Allen wrench to release the maintenance boom locking bolt. The subject's performance of this task was satisfactory.

Notes From Panel Film

Notes taken from the analysis of the films are as follows:

a. The subject's performance is better in each test conducted in respect to the sway and bounce of the foot and cage restraint attached to the far end of the maintenance boom.

b. Two handed locomotion along such objects as the antenna dish work very well. However, if a change of direction is required, as from the side of the rigid pole to the top, the subject handles the bounce by delaying traversing until the motion has dampened out.

c. Visual cues and color codes should be used on assembly and erection hardware to assist the worker in his tasks.

d. In this type of work, restraints may hinder the EVA worker by getting in the way of his work. The more mobility that is required of the worker, the more that this contingency is apt to be a hindering factor.

e. The difficulty noted in the records of the subject's trouble in positioning and orienting the panels to the antenna dish is not a product of the task sequencing, but a separate problem of motivation and subject control.

TWO LARGE RIGID MODULES

In the erection and assembly of the two large rigid modules at one-g, conducted to establish the task procedures and sequencing, it was evident that the hardware for this erection was not adequately designed to provide the type of erection essential to the simulation. Two major faults existed that were obviously going to interfere with the test. First, the module, when bolted together, was not going to provide the rigidity necessary for "good" EVA simulation. From the prior large module tests, the rigidity problem had been observed and found to be of considerable importance to the simulation technique. It appears mandatory, at least for water immersion simulation, that the connections and joining techniques used on the simulation hardware be made in such a manner that they are firm and tight without play and flexing at the connection. The erected large rigid modules lacked the required rigidity. Secondly, it was now known from prior tests that fastening, holding, and clamping were exceedingly difficult tasks to perform in the neutrally buoyant simulation mode. The fasteners used in the assembly had already proven difficult to work with. In addition, their placement on the supporting structure of the module was such that they were practically inaccessable to the pressurized glove of the subject. The feedback problem identified in the earlier tests for the bolt-wrench contact was obviously going to be a problem.

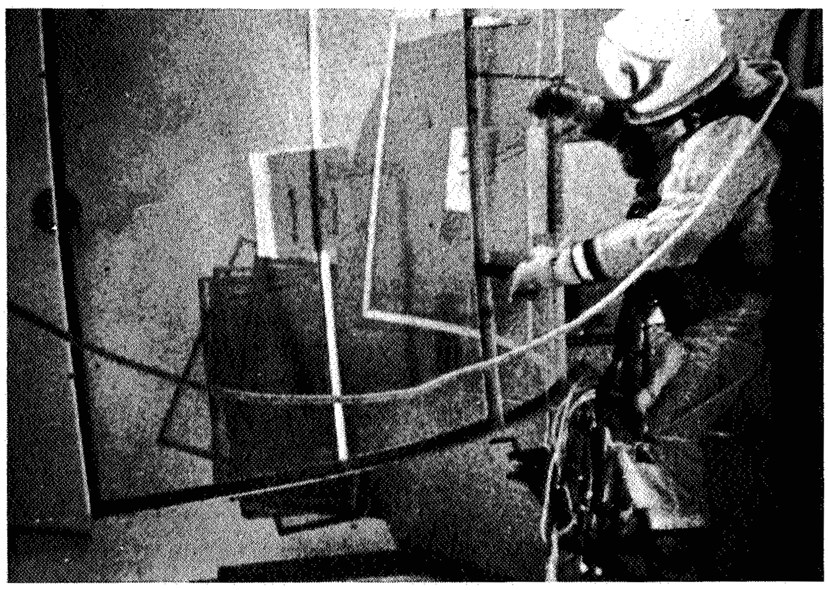
The subject had a gread deal of difficulty finding a tool that would permit him to grip the bolt heads (which were very close to the inside of the angle of the panel's structural member) and at the same time let his hand be far enough from the panel's surface so that he could turn his wrench. A ratchet with a long extension seemed best, but even this led to problems; the wrench slipped off the bolt head and the hand had trouble turning the wrench because of contact with the panels surface (Figure *5-43).* In addition, the length of the extension increased the problem the subject had with the lack of kinesthetic feedback of the action of the bolt head inside the wrench. The subject also had a problem with the arm-hand steadiness required to make bolt-wrench contact (Figure 5-43). All of these problems resulted in the subject having great difficulty in starting only a few of the bolts in the captive nuts. Many had to be started by a diver, after which the subject tightened them.

A second problem in putting the sections together was that of running out of hands (Figure 5-44). The subject had difficulty controlling the position of the second panel so that he could align it with the section he was hooking onto. With a different bolt location, large angle members, and possibly a better tool, the subject could have started the bolts with the hand that was not aligning the panel. The restraint setup, however, was such that the subject had to use one hand to change his restraint while he was still trying to start a new panel. The entire test made salient the need for better hardware. Some possible improvements could be handles on the panels so that they could be controlled easily by hand, panels and fasteners strong enough to support the worker from restraints hooked to the module he is building, and some developmental work with captive bolts and screws (Figures *5-44* and *5-45).*

The captive bolts were indispensible in that the job could not have been performed without them. However, they had the drawback of projecting from the panel in such a manner that made it hard to align a pair of panels and clamp them. The captive nuts were hard to start even for the divers. With the pressurized gloves of the suit it was even more difficult.

With the subject in the bird cage, a better restraint, he still could not start the bolts. Leg positions in the bird cage varied considerably as he worked. The freedom to rearrange his legs gave him control over his reach, work position, and the amount of weight he could take on an arm.

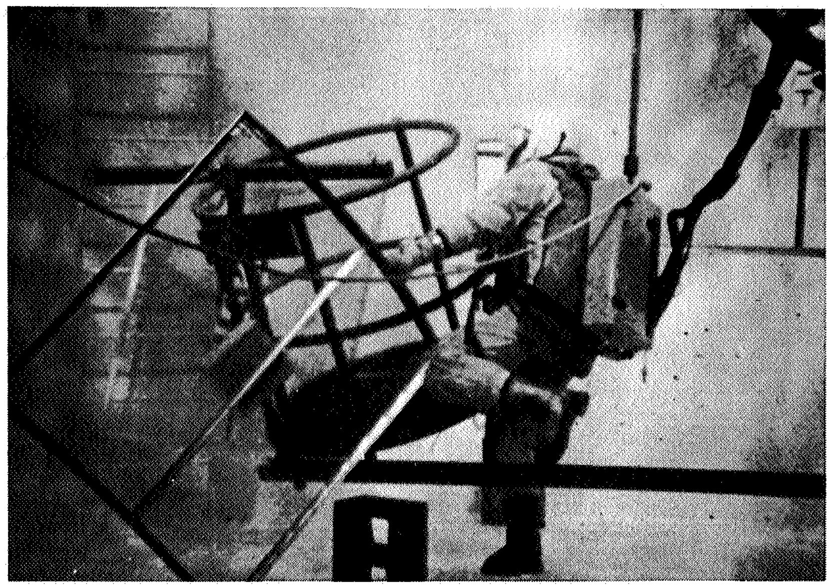
SUBJECT USING RATCHET TO HELP AVOID HAND CONTACT WITH SECTION



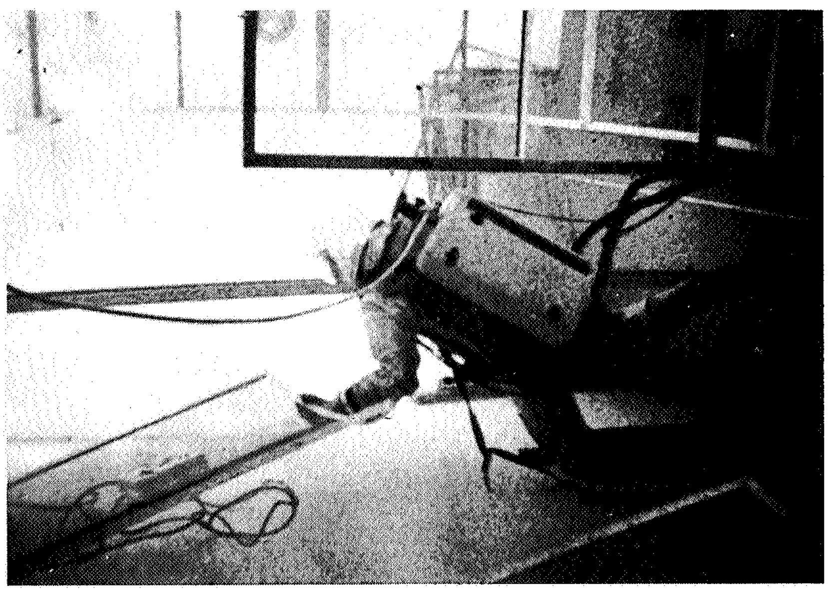
F-7332

BOLT/WRENCH CONTACT DIFFICULTY

Figure *5-43*

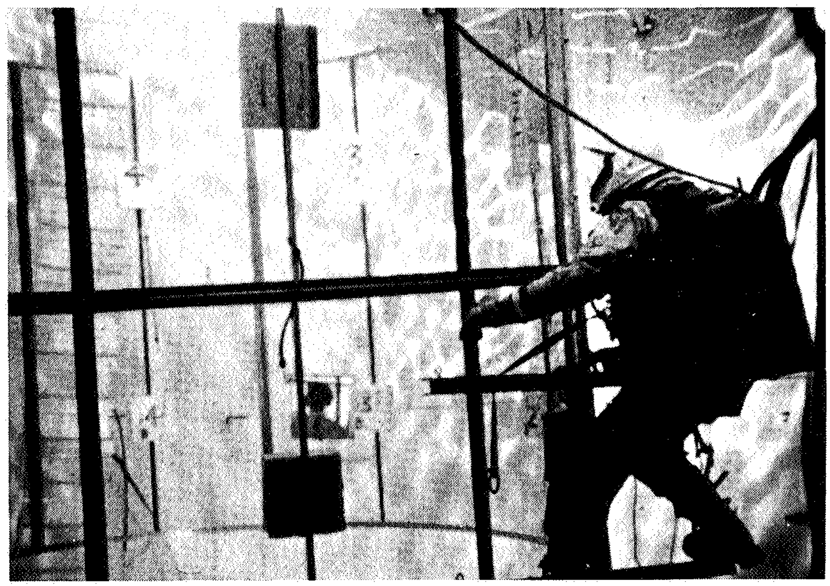


SUBJECT OUT OF CONTROL WITH SECTION IN HAND



THUMB AND FINGER GRIP ON PANEL DURING ONE HANDED TRAVERSING F-7333

Figure 5-44



F-7334

SUBJECT USING "T" RESTRAINT RATHER THAN CONNECTING RESTRAINT TO MODULE

Figure 5-45

The subject used the T-bar restraint at his own election. Once he was restrained, the subject managed to pull the two modules together and start both bolts (figure 5-46). Before the subject got the first bolt started, the observer had to interfere to get him to tighten up the module.

After the subject tightened several bolts on the opposite side of the rigid modules, the divers tightened those that remained. The last bolt was tightened by the subject (Figure 5-46) after he had rotated the module 180 deg. One notable item was the subject's use of one of his restraint connectors as a trolley to ride on the rope.

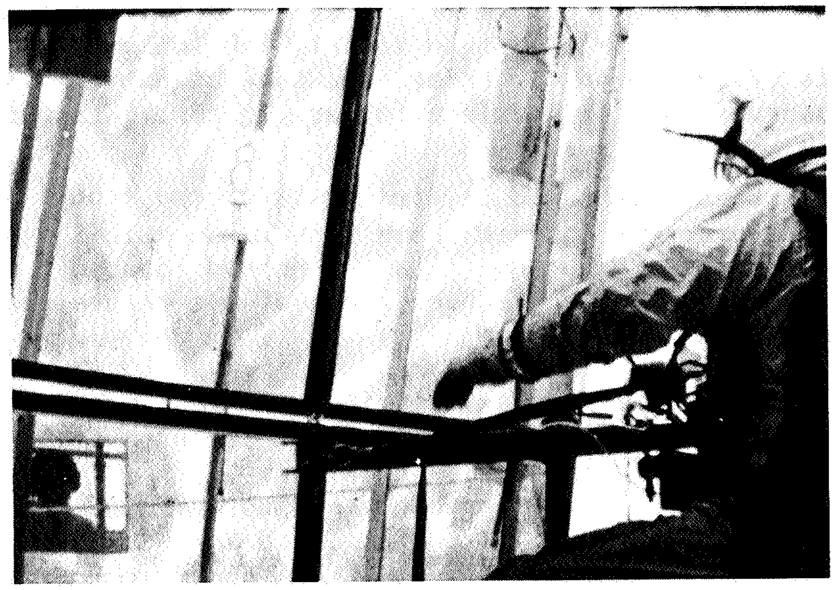
The fastening problem that existed for this test was a major one, The observations made on the difficulty the subject had with small bolts sizes were supported conclusively in this test (Figure 5-47). The handicap of the suit was a constant difficulty the subject had to overcome. The numerous interactions of fasteners, suit, restraints, and procedures accumulated into task difficulties, making the performance of the subject inefficient.

It is believed, however, that had time and cost allowed a redesign of the hardware, a procedure could have been established that would have allowed the subject to erect the modules without as much difficulty.

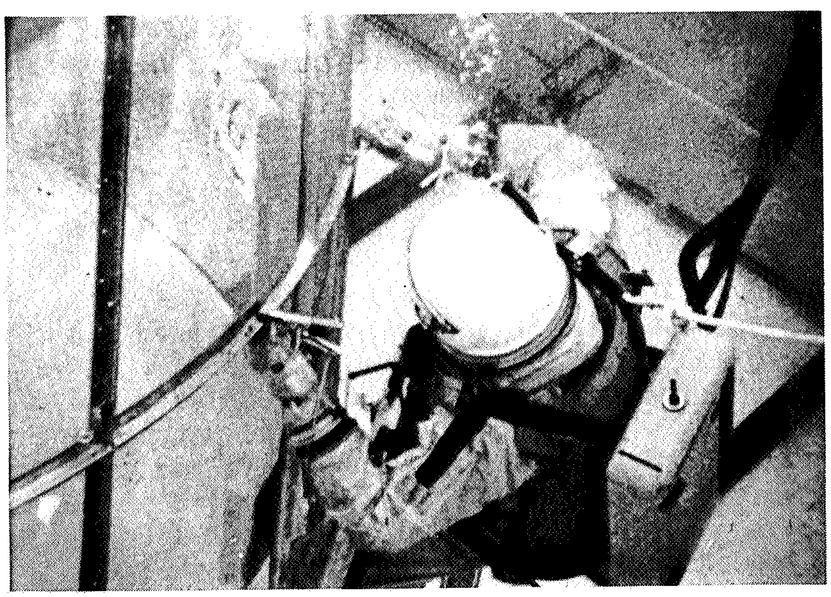
The above observations, although negative in nature, were made throughout the tests. They have not identified impossible tasks, but tasks that should be performed in a specific behavioral sequence within an appropriately designed man-machine interface. The problem posed is not one of eliminating impossible task requirements, but one of assuring that the tasks can be performed successfully by providing the hardware, procedures, and training necessary to assure mission success.

INFLATABLE MODULE

Since the step-by-step task sequences established for the large module tests had failed to produce the desired results, it was decided that a generalized concept for erection would be established and depicted for the subject by a series of elementary drawings illustrating the erection procedure in various stages of assembly. Prior to the actual erection by the pressure suited subject in the neutral buoyant state, the erection was performed by scuba divers. The subject did not participate in these tests, but was allowed to observe them through the observation port and make procedural changes he believed necessary. As in the antenna erection and panel application to the antenna, the subject was allowed to set the sequence for the erection. The schematic drawlngs and the prior erection were done primarily to show by "doing" and provide the subject with an opportunity to participate prior to the actual test condition. This participation of the subject was to take advantage of his creative critical contribution to the procedure and to provide a motivational factor from his participation.



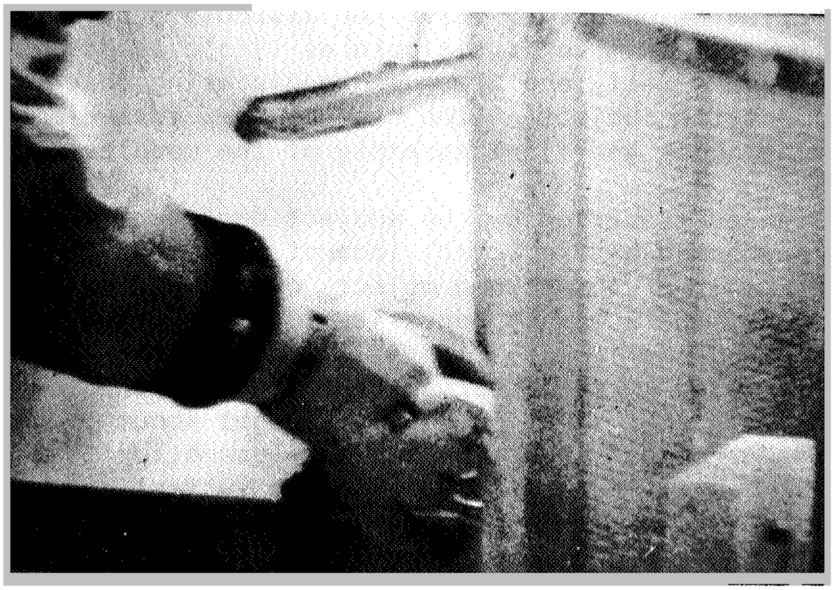
SUBJECT CONNECTING TWO MODULES TOGETHER



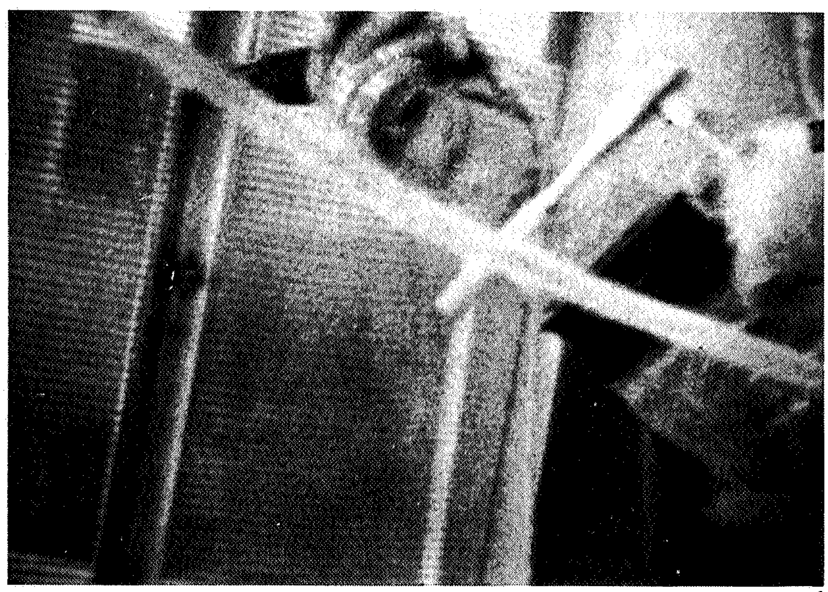
F-7335

SUBJECT USING OPEN END WRENCH TO TIGHTEN BOLT

Figure 5-46



SUBJECT USING THUMB AND FOREFINGER TO START BOLT



F-7336

SUBJECT CLAMPING TWO SECTIONS TOGETHER PRIOR TO TIGHTENING BOLTS

Figure *5-47*

The test orientation was to leave the assembly procedures to the subject, and for the test team to participate as little as possible, This procedure did not work well, and the human engineering observer found it necessary to direct the subject in the step-by-step task-elements of work necessary to bring about the final assembly of the modules.

Short distances traversed by the subject during this test were to a large extent performed by the "crab" locomotion movements. This was especially true when the subject had objects of the module in his hand. It was observed that there was no necessity for the subject to have his feet and torso in any particular orientation to use this locomotion method. It is believed by the observer that the frequent use of the "crab" traversing technique is at least partially brought about to keep the body away from the hardware that is being used for locomotion to prevent catching the suit on it. For example, when the subject had objects in his hand, he seemed to move and position that hand with more deliberation to assure himself that it would not hang up.

The ladder-locomotion aid was placed along the maintenance boom from the mockup to provide the subject with as many attaching points as possible for his legs and feet, and thus give him a greater degree of freedom to use both hands. However, it was a full 16 min into the test before the subject utilized the ladder-locomotion aid in the restraining manner expected. Instead, the subject seemed to prefer to connect his waist strap to a ladder rung and use this as a pivoting point to turn about in various positions. The change of position was carried out by forces applied mainly on the free floating inflatable modules (inflated at this time). This technique by the subject was a sudden shift of positioning technique from what had been developing progressively throughout the tests. The subject had sought to use his feet and legs to assist him more and more throughout the program, and now, in the last test where a special effort was made to provide the feet and legs with an object very adaptable to foot and leg contact, it was ignored and only used in a limited degree. No observations were made that can fully explain this change in positioning technique. The observer noted that when the subject did use the ladder for a second point of contact for positioning, it worked very well. On the other hand, without the second point of contact the subject assumed a type of free-floating position above the locomotion aid. This free-floating position added little to his capability to perform the work of the test.

The subject often dropped unattached hardware, which was retrieved by the divers. At one time, the subject was working while unrestrained with materials that were unattached. It appeared that the drag and damping effect of the water environment kept the subject fairly well positioned in one area--an obvious shortcoming of the simulation.

The subject had trouble handling and manipulating the connecting rods for the two inflatable modules. This was attributed to the lack of true neutral buoyance for the rods, their weight making the subject negative in buoyancy whenever he had one of them in hand. As has been previously stated, all equipment used must be neutrally buoyant to have valid simulation.

Listed below are noted observations from an analysis of the films taken during the large inflatable module erection tests.

Film Notes for Inflatable Module Test

a. The folded packages of the inflatable module, approximately I in. x I 1/2 in. x 1/2 in., was moved through the water with ease by the subject. There was no observable evidence of drag hampering the subject while traversing with the packages.

b. Since the subject elected to do much of his work without using a second point of contact, such as a foot or leg in the ladder, he was forced to do much of his work one handed. The nature of the materials and hardware did not lend themselves to this one-handed application, and the subject had more difficulty performing his work throughout the test than was necessary.

c. The subject used the technique of throwing the inflatable modules out away from himself to unfold them just as he had used with the folding panels, and it worked no better for the inflatables than it did for the panels. Such a technique may be satisfactory for actual space work, but it is not applicable to water environment.

d. When the subject is required to move and reposition his waist restraint, much time is lost due to the type of connectors used and the extreme flexibility of the strap itself.

e. The trouble compensating for the limited and distorted visual field while under water during the maintenance tests was of even greater significance during the large module tests. It is assumed that this is partially due to the difficulty the subject had in not being able to observe his work from a distance as it progressed.

f. As in the prior tests, there was a considerable amount of boom action. The subject adapted to this very well.

g. If similar inflatable modules are used in future testing, an attempt should be made to use the inflation of the modules as a partial means of positioning the modules as they are being inflated.

h. Since all locomotion devices seem to work reasonably well, the guide rule for selection should be one of simplicity.

i. Carrying packages in one hand while traversing is an uneconomical way of performing work in the water immersion simulation, and an effort should be undertaken to correct this by providing attaching points to the suit or other suitable means for transporting materials in a manual manner.

GENERAL COMMENTS ON THE LARGE MODULES

For the tests of the large module erection and assembly, one of the faults with all of the hardware was that the connecting points in the assembly did not provide a rigid joint. The joints, connections, assembling points, and fastenings in each modular configuration had some degree of flexibility. As the assembly of the module progressed, these connecting points would compound the total "play" or give in the module. This lack of rigidity would prevent the subject assembling the modules from working to the "best" of his ability. The work required to overcome these hardware faults consumed much of the subject's time and energy. It has been pointed out repeatedly that the fastening problem identified in this study effort is one of paramount significance. It is of equal importance, in respect to water immersion neutral buoyancy simulation, that the hardware used during these large tests realistically represent the configuration they are to depict if the dynamics being sought are to be observed and isolated.

The obvious and primary observation to be made from the totality of the large modular tests seems to be that the mobility required of the worker to move about the modules to the various work stations is possible Also, the types of modules tested all appeared to be feasible concepts from the results of the simulation used. The study effort showed that EVA concepts can be tested in this manner. It is concluded that the testing must be conducted with real or as representative hardware as possible. Hardware inadequacies tend to invalidate the tests to the point that it is often impossible to isolate the subject's work capabilities and limitations. Because of this, firm conclusions and observations frequently cannot be made where several components of hardware interact simultaneously. This limitation has in effect been a boundary that has resulted in setting the stage for an appropriate test methodology to obtain the isolation of the variables necessary to assure an acceptable degree of confidence in the observations of the man-machine dynamics.

SUSPENSION SIMULATION, MAINTENANCE TESTS

The task sequence selected for this test was a composite from the easy, difficult, and hard tests of the water immersion tests. This procedure was used since the tests all include a considerable amount of traversing. The simulation by suspension makes traversing, due to hardware interference, almost an impossible task. It was believed that little could be learned from the traversing in this test mode, and a great amount of valuable time would be lost if locomotion conditions were kept in the test format. The decision to eliminate these from the tests permitted the test to include all three test levels in one sequence of tasks.

The pivoting of the subject on the first two gimbals of the simulator were far from a true simulation of weightlessness. Motion pictures of weightlessness from the Gemini program show the astronauts moving with a certain flow and a prediction of movement and recovery. This aspect also is evident in water immersion simulation. This condition did not exist in the suspension simulation. In the balanced condition the subject would tend to pivot the instant he moved one of his limbs. This was especially noticeable in the forward reaching motion. The subject would counter the tipping forward by pushing back from the mockup with his hands. He could work with his hands in the mockup by giving himself little shoves with thebacksof his hands to keep a rocking motion going that tended to keep him in position. The subject also relied on the technique of holding on with one hand and working with the other hand when possible. The configuration of the suspension simulation hardware allowed the subject to place one foot up on the hand rail of the mockup. This second point of contact often provided enough stability for him to perform the task. On some occasions the subject could not perform the work when in this position. When this happened, the subject would generally go to a less desirable position, such as placing his head inside the top edge of the mockup opening and placing tension on the front of the mockup with his toe. The "breaking" of these positions was always sudden and sometimes almost violent, due to the tendency of the subject to pivot on the gimbal. The pivoting of the subject from his center of gravity was so sudden in the left and right and the forward and backward motions that they resembled falling.

The basic conclusion that can be drawn in comparing the suspension simulation with the water immersion simulation is that the suspension simulation state-of-the-art hardware does not appear to give nearly as realistic a "picture" of weightlessness as does water immersion. This conclusion is in reference to tasks, work, and motion aspects. The in-place technique used by suspension Simulation for specific tasks repeated over and over in a simple manner is an excellent technique for obtaining energy expenditure data. It is obvious that suspension simulation is not appropriate for the study of the motion dynamics involved in EVA work.

The subject performed eight tasks the first day of testing. Of these eight tasks, seven were performed using the technique of placing one foot on the hand rail to maintain a stable working position. In the second day of testing the tasks were mainly dexterity types and the subject worked these by binding the top of his helmet inside the upper edge of the access opening. The dexterity tasks were performed by the subject without pulling his Gemini XII type strap restraint taut. It is felt that this was possible because of the great resistance against up and down and back and forth movements of the overhead trolly. The major difficulty encountered was the tendency to tip forward into the work when the subject became unbalanced by extending his arms forward. The subject handled this tipping in the same manner as before, by pushing back with his hands to keep a rocking, balancing motion that allowed him to work with his hands while at the same time keeping himself positioned in front of the mockup.

EVA WORK

General

Traditionally, work improvement studies have concerned themselves with the "economy" of the work situation. The objective of such studies was to reduce the physical effort, eliminate waste motion, and to speed the handling of materials. The basic purpose was to find a means of increasing production. This study is concerned with many of the same aspects of performance. However, it was designed to ascertain the scope of possible human manual activities in the weightless envi'ronment.

The observational analysis was performed on two levels. The first and primary level was to observe and record the dynamics of the motions used by the subject to perform the tasks within the multiple, restrictive contingencies of the test conditions. The second level of observation dealt with work improvement and consisted of two aspects. One aspect was to observe, record, and analyze the work improvement techniques used by tne subject with the criteria that these innovations must indeed be positive contributions and true "work improvement." The second was to isolate those work improvement innovations that failed to contribute to the procedures. These would include mistakes in judgment, failure to follow instructions, and poor insights. From these observations it was believed that a beginning could be made toward establishing a set of ground rules for the EVA worker that would assist the engineer in providing a hardware design that would interface with the EVA worker in the best possible manner. Thus, the astonaut would be more aware of his work limitations and capabilities.

Worker Positioning

A good work position is defined in terms of the task to be performed. All good positions require stability, freedom of limb movement appropriate to the task, good vision of the work area, and the capability to apply the dexterity and muscular force necessary to perform the task. What may be a good position for one task may not necessarily be a good position for another task. For example, the subject may have to be very close to his work or be backed off to his maximum arm reach. The good position is one that does not interfere with the task in any way and allows the completion of the task in an effective and satisfactory manner. A comparison is presented in Figure ***5-48.***

Two-Hand Work

The use of both hands to perform a task seemed to be a function of position stability. The more stable and secure a position, the better the subject's performance. The poorest performance for two handed tasks occurred during use of the rigid leg restraints and the best performance during use of the foot-strap restraint and the cage restraint.

Task Sequence

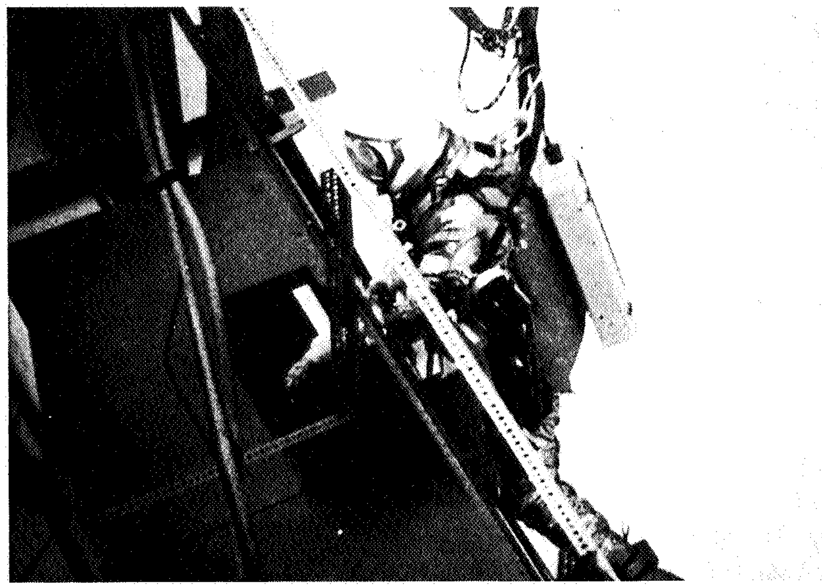
The subject would occasionally take short-cuts in the task sequence that appeared to be work improvement steps However, these deviations from the task procedures most frequently lead to difficulty. For example, when the subject was instructed to return a wrench to the tool kit and then remove the loosened bolt with his fingers, he did not return the wrench to the took kit, but held the wrench in one hand and removed the bolt with the other. He then found himself in the awkward circumstance of having the bolt in one hand, the wrench in the other, and unable to manipulate his restraints to get to the tool kit to store the wrench and bolt. The human engineering observation reports taken during the tests contain a number of similar observations. It is for this reason that a strong recommendation is made that all EVA tasks be checked out in detail by simulation prior to space application.

Restraint

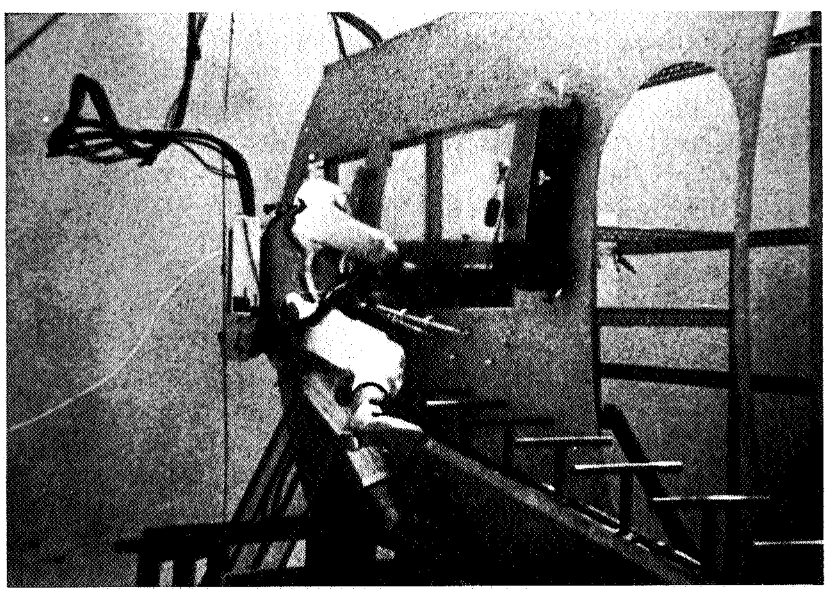
Generally, the effectiveness of a restraint is inversely proportioned to the amount of time the subject spends seeking and obtaining the best position from which to work.

Positioning and Holding on

One of the best positions that the subject can assume is one in which he is restrained, able to use one hand to hold onto something solid, and able to use the other hand to perform the task (Figure ***5-49).*** This provides the subject with a two-point contact at the work station and the



GOOD POSITION FOR PERFORMING TASK REQUIRING
SUBJECT TO WORK IN MAINTENANCE BOX



F-7337

POOR POSITION FOR PERFORMING TASK REQUIRING
SUBJECT TO WORK IN MAINTENANCE BOX

Figure *5-48*

F-7338

GOOD POSITION MAINTAINED BY HOLDING ON WITH ONE HAND

Figure 5-49

stability necessary for good work. Difficulty arises when the subject attempts to carry the one-handed work into tasks that require both hands for satisfactory performance.

The number of times the subject found it necessary to maintain his position by hanging on to the mockup with one hand while working with the other was much greater than expected. This was partially due to the fact that many of the two-handed tasks were "broken down" by the subject into adaptive task-elements that could be performed with one hand.

Simultaneous Use of Tools

The requirement for the EVA astronaut to use two tools simultaneously should be eliminated wherever possible and special restraint provisions provided when this cannot be avoided.

Rest Periods

Rest periods for the EVA worker will be essential. Consideration should be given to establishing scheduled periods of rests rather than allowing the EVA astronaut freedom to establish his own rest needs.

It is the judgment of the subject that the rests required are not an effect of the actual physical work associated with the task, but rather the result of performing the task in the pressure suit where additional contingencies are imposed by the resistance of the suit, the restraint and weight shell, and the limited covering capability of the ventilating gas.

Opposing Arms Work

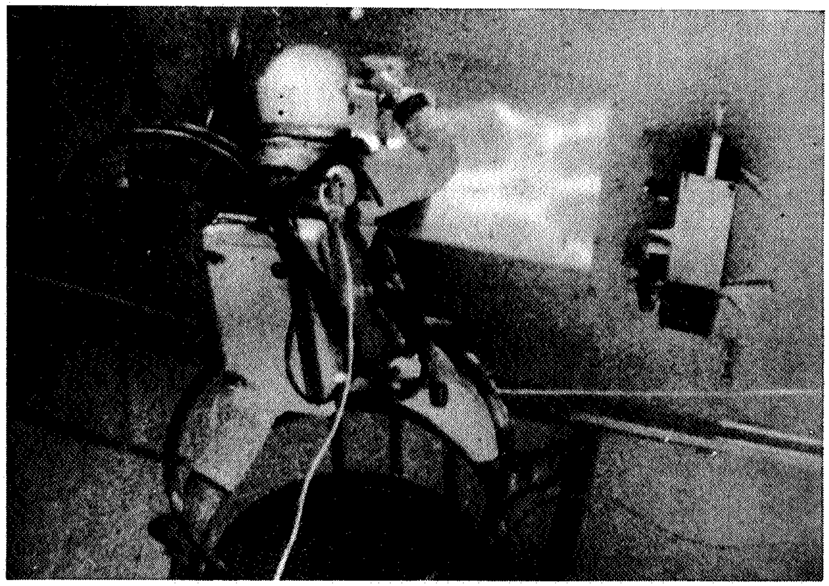
When the task allowed the use of equalized force applied by the use of both hands or arms opposing one another, it was performed without difficulty. The use of the bolt cutters is a typical example.

The Hand Tasks

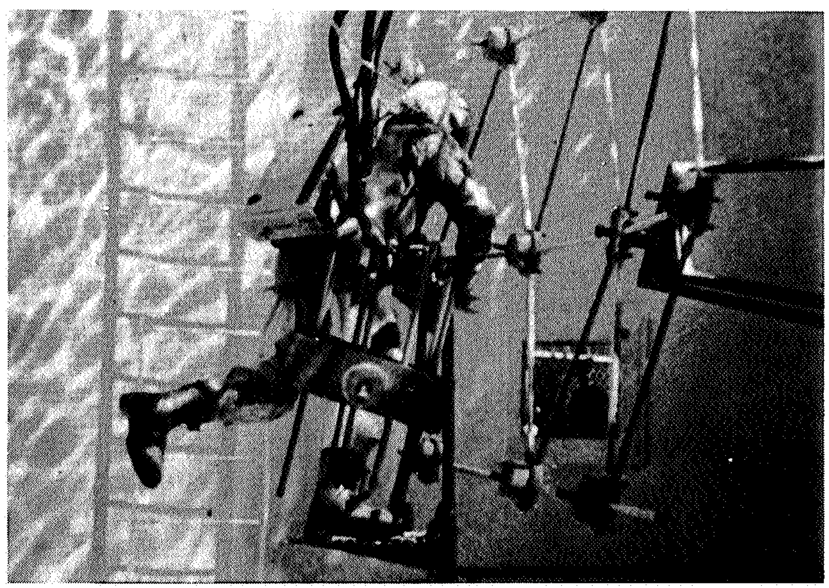
The two handed maintenance tasks were more often attempted by the subject with one hand when he was using the rigid leg restraints than when he was using either the foot-strap or cage restraint configuration.

Cage Restraint

The work improvement innovations used by the subject during the tests conducted with the cage restraint concept were very effective. The majority of these innovations involved gett-inq into positions that allowed the most effective work performance (Figure 5-50). At first, the



UNUSUAL TOE, HAND, AND ANKLE CONTACTS TO
OBTAIN A POSITION HIGH OUT OF CAGE



F-7339

SUBJECT REACHING THROUGH ANTENNA
STRUCTURE TO TIGHTEN THUMBSCREW

Figure 5-50

observer was inclined to attribute this work improvement to the subject's learning during the repeated performance of the tasks. However, later tests conducted with various configurations of the rigid leg restraints were performed in the same difficult and troublesome manner as the earlier tests with these restraints. The improved performance in the cage was therefore considered a function of the restraint being used. This consideration is the reason for recommending further development of the cage restraint and continued testing in the water imnersion simulation technique.

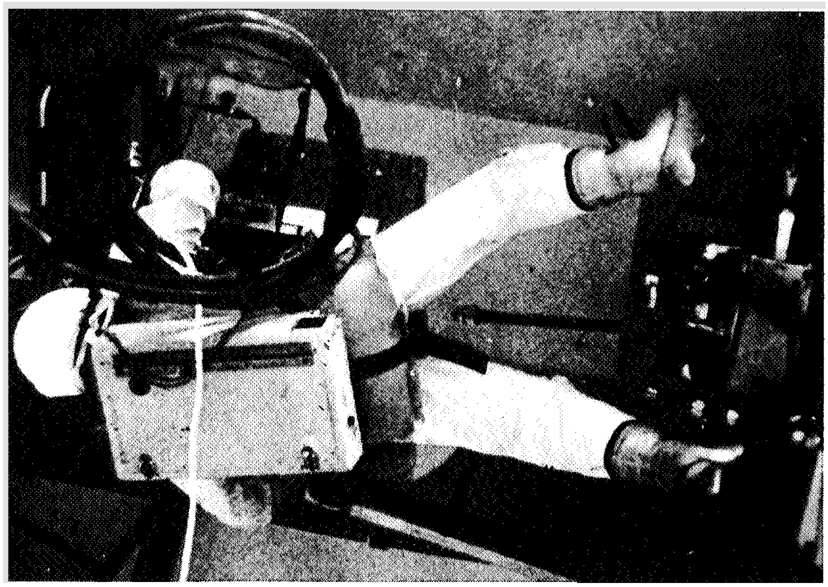
During the conduction of Test 1.3.4.4. (1. Underwater 3. Hard maintenance test 4. Taut rope 4. Cage restraint), there was a sudden use of new work positions. These were the prone and the horizontal positions assumed over the top of the cage. Much of the positional control for stability was obtained by the subject intertwining his feet and legs around the top rung of the cage restraint. One observer stated that the subject seemed to use the cage as a series of leg and foot holds. This, of course, was the intent of the cage restraint concept.

Positioning

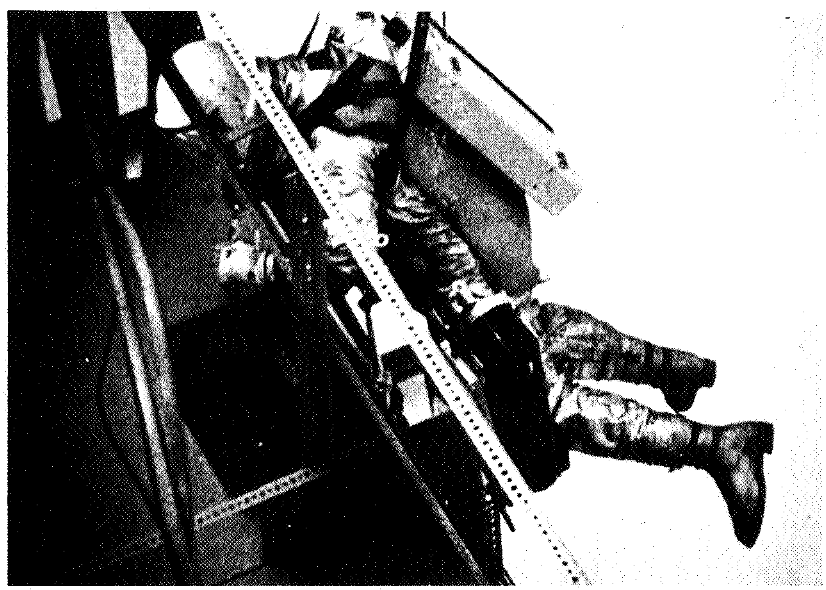
The majority of the successful work improvement innovations used by the subject were in relation to securing more stable work positions (Figures **5-51** and 5-52). The least successful work improvement efforts that the subject engaged in were those associated with alterations of the task sequencing of the tests. As the testing progressed, the subject engaged in more and more deviations from the task sequences. Some of the deviations were positive short cuts that actually shortened completion time and improved the performance of the task. For the most part, short cuts gained the subject little and caused trouble and difficulty that he would not have encountered had the followed the step-by-step procedures, Factors partly responsible for this motivation include the increased risk with increased exposure, the hot and sweaty environment, the fatigue and frustration, and the psychological reaction to the stress inducing conditions.

Task Sequencing

The tests establish quite conclusively that neither the subject nor the human engineering counterpart can completely lay out the best means of doing a relatively complex sequence of tasks in a work performance situation. The tests also establish that the functional sequencing performed at the paper and pencil level prior to testing was indeed essential to the structure of the test. Much of the conflict between tools, fasteners, and work positioning was foreseen at this level and provided for. However, the test of adequacy is in the performance. The performance of the worker must be evaluated in the actual work situation. For this reason, it is recommended that anticipated EVA work tasks be performed in water immersion simulation before the final procedures are developed.



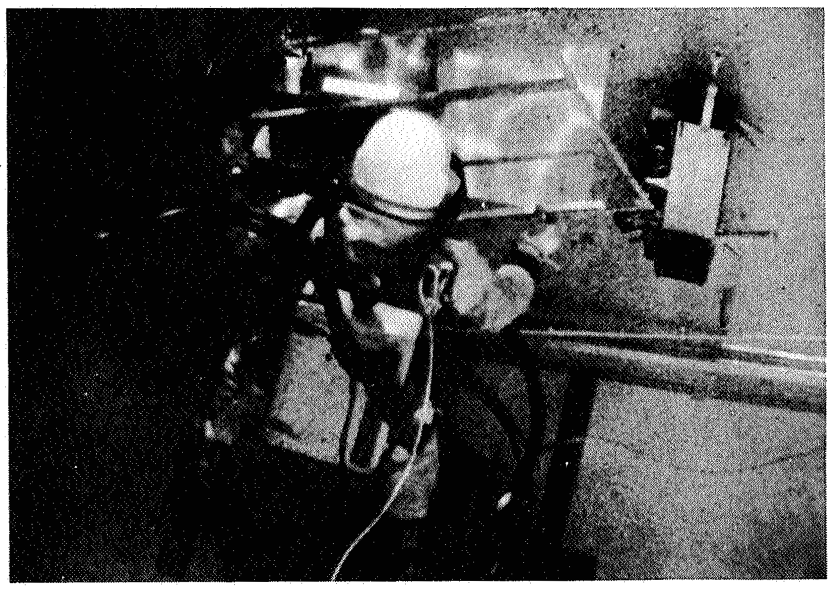
SUBJECT REACHING INTO MAINTENANCE
BOX FROM SIDE POSITION



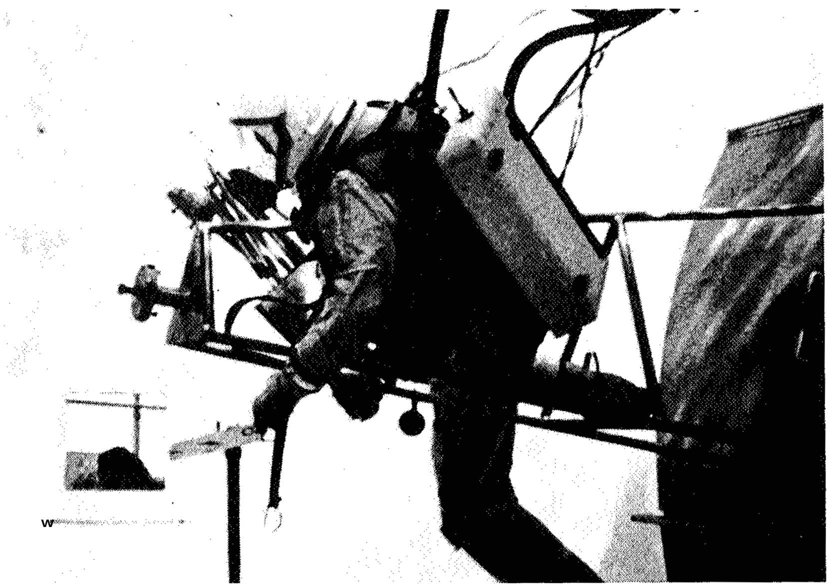
F-7340

SUBJECT PUSHING AGAINST RIGID LEG RESTRAINT WITH
HEAD WEDGED UNDER EDGE OF ACCESS OPENING

Figure 5-51



SUBJECT INTENTIONALLY FALLING BACK INTO CAGE WITH BOTH HANDS ON ACCESS PANEL



F-7341

SUBJECT STRADDLING MAINTENANCE BOOM AND USING ANKLE TO MAINTAIN POSITION SO THAT BOTH HANDS ARE FREE FOR WORK

Figure 5-52

Comments by the Subject

Notations from the human engineer's test report support the conclusion that the subject is not the most objective source of information. The subject commented that the foot-strap restraints were the poorest restraint device used. However, task performance does not support his conclusion. The foot-strap restraint was one of the better restraints used. The successful completions of the difficult and hard task-elements were much more successful with the foot-strap restraint than with the other restraint configurations, although the cage restraint was almost as effective.

At the conclusion of each test the subject would be extremely fatigued and a degree of hostility would be evident that was almost always projected toward the members of the test team. At these times the subject's comments were of questionable validity. The subject was not always aware of the functioning of his restraint device. At one time the observer asked him if the waist restraint strap was taut. The subject said that it was not, even though the observer could see that the waist strap was indeed taut. Another comment of the subject was that the hand rail along the front of the mockup was of more use in actually performing the tasks than was the foot-strap restraint. However, this is not borne out by point of analysis. The foot restraint provided the subject with the freedom to position his torso for work in almost any position he wanted. It also allowed more frequent use of two hands that resulted in improved task performance and reduced times.

In Test 1.1.5.5. (1. Underwater 1. Easy Task Sequence 5. Rigid Pole 5. Foot Restraint) the subject tried a work short cut by relea- 3 his restraint prior to freeing the maintenance box. As a result, he found himself with the box in one hand and hanging on to the hand rail with the other. In this instance, he could not traverse to the hatch as required by the next task. The subject did not like the rigid leg restraints because they were troublesome to move from one connecting point to another on the mockup. This is a valid criticism. Another valid observation was that the restraint configurations tested were not realistic enough to be acceptable for actual EVA work.

Pressure Suit

The pressure suit is a constant hindrance to work, requiring compensating positioning and extra muscular exertion. This, coupled with the visual limitation, combine to make the most simple work tasks difficult. Fatigue sets in early, almost as soon as the subject begins work. The combined disadvantage is most evident in tasks requiring the repetition of the same arm motion over and over. The use of the screwdriver and the wrench are good examples. Throughout the tests when these tools were used, the subject would develop arm cramps and require frequent rests, and would work the arm back and forth to remove the cramp. To counteract this effect, the subject would try to change the tool from one hand to the other, but the left-hand work could be performed successfully only for some tasks and only when the subject was positioned well. The cases of work being accomplished with the left hand were very limited and occurred only when the subject was using the cage or foot-strap restraint configuration. These restraints would allow the necessary freedom of body positioning required to do right handed tasks with the left hand.

The binding effect of the suit on the arms when the subject was doing work directly in front of himself caused the subject to seek positions where he could bring his arm into this frontal work from a side approach (Figure 5-53). This seemed to allow the arm to move in the suit with less resistance. The subject would do this in the work situation without being fully aware that he was also turning his upper torso either left or right. The fact that the subject could do this with the one-leg restraint, but could not do it with the two-or three-leg configuration, may be the reason for his preferring the one-leg configuration over the others, even though the two-and three-rigid-leg restraints provided a more stable position from which to work.

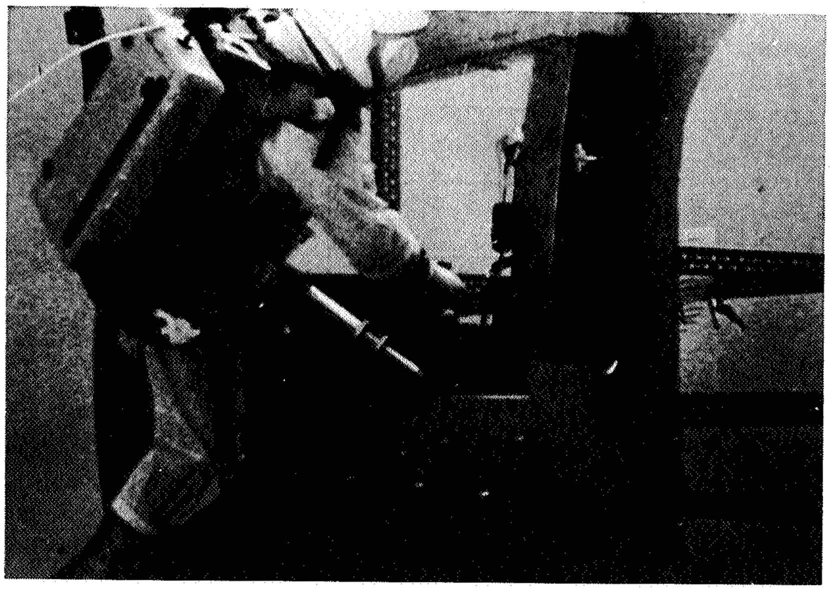
If the subject was working on small items such as bolts and wires, he had little, if any, feedback from the object through the glove. Generally speaking, if the subject could not see what he was holding and manipulating and the item was too small for feedback through the gloves, he was not able to do the task.

Stability

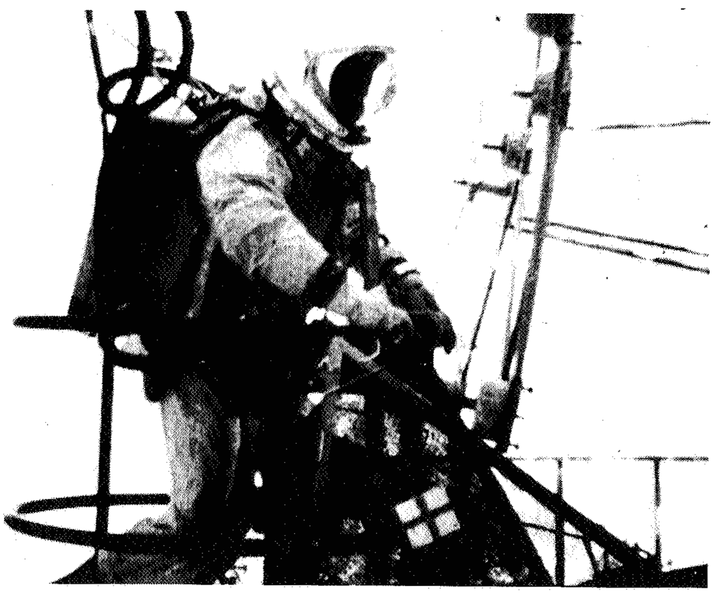
In the final analysis, both dexterity and force were dependent on the stability of the subject's position, although correct placement of the torso to the work is also essential (Figure 5-53). Without these two positional factors, tasks requiring fine dexterity or considerable force could not be performed by the subject. In cases where the subject was not stable, the fumbling and loss of tools was very evident as compared to those cases in which stability existed. If one major conclusion is to be made from this study, it is that the subject was either stable when performing work or was seeking to stabilize himself so that he could perform the work. The compromises were many and deviations and innovations frequent, but the underlying necessity of positioning stability and the subject's body position in relation to his work were always present.

Presentation of Work to Subject

In the tests of the antenna, folding panels, large rigid module, and inflatable module, the worker was presented to the module when it may have been better to present the module to the worker. In the workaday world where large objects are being assembled, the worker moves along the structure making his connections and creating the assembled object. The necessity for this is obvious since the economy of moving the worker to the work spots is the common-sense approach. Some deviation of this is found in large production plants where assembly line techniques are used but, for the large part, the operator is presented to the work. In the weightless condition it might be advantageous to present



SUBJECT ATTEMPTING TO GET POSITION
FOR SIDE APPROACH TO WORK



F-7342

TYPICAL GOOD POSITION IN CAGE RESTRAINT

Figure 5-53

the object being worked on to the worker. Two advantages may be gained by such an approach. First, since the work capability is so dependent on the positioning and the stability of the worker, it is possible that it would be more economical in a large module assembly situation to move the hardware to the worker when he has good positioning and stability. Second, the control and presentation of the work (in this case, the large module) to the worker may be the best approach because of the weightlessness of the object making handling and movement less difficult.

NECESSITY OF SIMULATION

The repeated performance of the subject during the maintenance tasks of taking out the same bolt and positioning to the same difficult or awkward work point provided practice and learning that was not available to him during the erection and assembly of the large modules. It is possible that had the large module task sequences been repeated over and over, the subject would have learned to cope with the problem of handling and manipulating the small objects. Even so, there are two conclusions to be drawn that are extremely important to the delineation of the EVA worker's capabilities and limitations. The first, and the most important, is the benefit derived from practice of an EVA type of task in an appropriate simulation condition. The second is that care must be exercised in selecting hardware for EVA use. Currently, the most feasible means of assuring that the EVA worker is not handicapped by either of these contingencies is to initiate a program of simulation with actual "space" hardware.

There were no observations made of the neutrally buoyant subject during the assembly of the antenna dish that pointed out or implied that the same type of erection could not be performed in space. However, much was left to be desired in this first experimentation of the assembly of a large module in the water simulation mode. These shortcomings were to a large part relative to the hardware configuration tested and the lack of proven procedures. However, the fact that these negative aspects existed and the tests were still successfully performed supports the position that erections and assemblies of this type may be performed in space. The one contingency is the adequacy of the simulation mode itself. The feedback evidence from the later Gemini flights, although not an adequate sample, were indeed favorable since the EVA astronaut had been subjected to water immersion-neutral buoyancy training; he believed that this experience was beneficial to his actual space tasks,

Simulation of the nature being used during this study does not provide positive proof. At best, it gives the observer behavioral sequences for comparative analysis. It is important that the conclusions and recommendations resulting from this study are not interpreted in the light of direct space application, but rather in the light of preparation for space activities. This is the intent and the orientation of the tests of the large module erection and assembly.

The first conclusion drawn by the observers of the antenna erection test was that the interface between the EVA worker and his hardware is the key to the success of his task. (A certain amount of this opinion is carried over from the observations made throughout the large modular tests.) The concern here is with the difficulty the subject had in handling and manipulating to a satisfactory level the off-the-shelf hardware used throughout the tests. It is recommended that all hand tools be adapted to the pressurized glove. The same is mandatory for fasteners. Small bolts and nuts were a continuous source of difficulty for the subject. Actually, this was true for practically all off-the-shelf hardware which has been designed for use by the ungloved hand. Planning for EVA, the man-machine interface will require a close systematic analysis of every manipulated object throughout its total EVA application.

No objection is expected to be advanced against the man-machine interface study for EVA. It is possible that objections will be raised as to the depth of analysis required. The position taken, as a result of this study effort, is that no object, including tools, fasteners, and hardware, will be considered acceptable without proof of acceptability testing by simulation. The general conclusion from the tests conducted imply that little of the hardware used is acceptable in its present off-the-shelf configuration.

RECOMMENDATIONS

An additional level of analysis from the AiResearch study is warranted in reference, to specific hardware that needs development. Examples of hardware faults are discussed in the following paragraphs.

The cage restraint is a promising restraint concept. The configuration tested was, however, too large to serve its original intent. It is recommended that its design be altered to an adjustable concept that would allow the cage to be expanded or contracted in diameter and that provisions be made to lengthen or shorten it as well. This would provide an opportunity to observe the restraint configuration in several space volumes with one piece of hardware and at the same time provide observations of the feasibility of using an adjustable cage concept as an EVA restraining device.

The foot-strap restraint is also a promising concept. The observations made during the tests pose the possibility of improving its function by providing a means of holding the foot within the stirrup in a firm manner. However, a means must be provided for the operator to disengage the holding mechanism in a simple and quick manner. There are approaches to this that appear to be relatively simple, such as a clamp that engages the sole of the shoe by a push-pull cable mechanism. It is believed that such a system would greatly improve the foot-strap restraint. It is also suggested that the capability for either stirrup to engage either foot be retained, and the holding device for the foot be so designed as to allow the switching of one foot or another to either stirrup.

Several approaches were used early in the program to design the rigid leg restraints so that they would be rigid at both connecting points, that is, on the suit fiber glass shell and at the mockup connecting point. Attempts to use large expando pins, vacuum activated vises, and a lockable universal all proved inappropriate. A compromise was used in tests where the lockable universal joint was used on the fiber glass shell at the suit, and a snap and eye connection was used at the other end of the telescoping restraint. The freedom provided at the snap and eye connection was totally unacceptable in the water immersion simulation mode. It is recommended that the rigid leg restraint be subjected to a design effort that will provide the rigidity required to keep the user stable and in one position by providing the locking connections at the suit and the work station. Some type of lever-activated, locking universal joint seems to be the approach to this problem.

Strap restraints at the waist of the subject were not satisfactory when used alone but were effective and essential when used in conjunction with the foot-strap and cage restraints. Their continued use is expected in any restraint mechanism to be developed and tested. In the configuration used in this program the mechanism for lengthening and shortening the straps was too small for adequate handling by the pressurized glove.

The fasteners for assembling the large modules were too time consuming, and a need exists for a positive locking, quick connecting fastener that can be engaged very simply, preferably without a tool. If a tool is required, a simple levering action is preterred over the torque action used with nuts and bolts. It is recommended that the size of the fasteners be kept large enough for good handling dexterity with the pressurized glove. To establish this size samples may be manipulated in the pressurized suit at one-g. The only fastener found in the AiResearch fastener review that seemed to lend itself to the fastener requirement was the trade name "Expando Pin." This fastener proved unsatisfactory during our tests and could not be used extensively. However, it was not the fault of the fasteners. The materials used for the modules was aluminum and it was, as a rule, thin and soft. When the bushing of the expando pin was locked in the holes drilled in these materials, it would expand the hole and the pin would not fit tightly enough to maintain a good connection, This pin does meet the basic fastener requirements for EVA and most certainly should be tested by water immersion simulation with appropriately designed fastener seats.

Other off-the-shelf fasteners appropriate for EVA assembly and erection may be available, but they were not found during the review of fasteners. If off-the-shelf fasteners are not available that properly meet the need of EVA work, then a specific hardware design and verification problem exists.

The clamps tested proved to be a paramount problem. The need for clamp tools to hold and retain objects in the weightlessness of space is obvious. However, this same weightlessness condition requires that the clamping task be performed as a one-handed operation, since the other hand must be used to position the object and hold it in place while the clamp is engaged. Thus, a design requirement appears to be evolving that requires a clamp that can be positioned, adjusted, engaged, and released all with one hand. None of the clamps tested met these requirements. The vise grip pliers came closest but proved unsatisfactory because of the large throw of the handles and the need for two hands to adjust the size of the jaw opening.

To alleviate the clamp problem, retaining lanyards were used considerably throughout the tests. These were a simple configuration of nylon cord with a metal slip ring or snap connection. The cord and harness snaps worked quite well, but the drag effect of the water environment and gravity was always acting on the objects retained in this manner. It is therefore, questionable whether retaining lanyards would prove satisfactory in space. Elastic cords were also used and in a limited way worked quite well for holding and securing objects during the tests. Their functional capability in space is also questionable. Small objects such as tools, bolts, and fasteners were especially difficult for the test subject to control and secure, and appear to be a separate hardware securing problem.

The design of off-the-shelf hand tools, conceived to be used only by an unrestricted hand, are not acceptable for use in performing work in a pressure suit. Although the tools were in general successfully used to complete the task, they did not provide an acceptable gloved hand interface. Hardware of this nature--i.e., manual hand tools for EVA--warrant special design effort to accommodate the pressurized gloved hand of the EVA worker. In addition, all the tools tested were not altered to neutrally buoyant objects. In tests where water immersion simulation is used and a large variety of hand tools were tested, there is a great deal of expenditure required to design them as neutrally buoyant objects. When the weight of the object is equal to several pounds, subjects' handling and manipulating become negative. The added effort of overcoming this slightly negative buoyant condition is an additional test variable that creates difficulty in interpreting the results. Achieving neutral buoyancy for the large module materials does not appear to be nearly as difficult a problem as for the tools.

The numerous negative observations made of the hand tools used in this study point out the need for appropriate power tools to be used in EVA assembly and erection. The applicability of power tools will be defined by the function to be performed by the EVA worker compared to the same task being performed with hand tools. If the activation function requires considerable force or repeated torquing, then power tool application to the work is warranted. The "economy" of using power tools is primarily influenced by two aspects: the time saved by the use of power tools over manual tool application and the saving made in the energy expenditure of the EVA worker in performing the task.

It is obvious that some work anticipated for EVA will lend itself to power tool performance and some will not. This again points out the need for definitive task analysis of EVA programs conducted in conjunction with neutral buoyant water immersion simulation so that the best and most "economical" manner of performing the work can be established.

Several programs are currently under way to develop the anticipated EVA power tools. Their functional capability must not be overestimated by pretest assumptions that they will fulfill the major requirement of the EVA worker in his assembly and erection tasks. The need for fitting, holding, moving, and positioning the hardware to be assembled will still require hand-to-hardware contact. Power tools will not fulfill the tool requirement for all tasks. In all likelihood the function served by power tools for EVA work will be similar to that function performed by hand-held power tools in the work-a-day world. Tasks requiring large force application for a considerable duration lend themselves to power application. This is also where power tool application will be most functional in EVA work.

In light of the recommendation for power tool application and the requirement for water immersion testing, consideration should be give to adapting the current EVA power tools and those forthcoming to the water environment.

Restraints

a. The lineman's position, or variations of it, was the most sought-after position used by the subject.

b. The effectiveness of a restraint configuration is inversely proportional to the amount of time the subject spends seeking and obtaining the "best" position from which to work.

c. Both dexterity and force are dependent of the stability and the positioning of the subject.

d. The foot-strap and cage restraints were generally better than any other restraint concept tested.

e. Stability of a work position is proportional to the number of limb contact points the subject can obtain.

f. Restraints that require many connections and disconnections during positional changes are too time consuming.

g. Restraints with free pivoting at connection points are undesirable.

h. Stable positioning required the use of hands and legs to maintain the position.

i. Two-hand freedom is essential for "good" EVA work and is dependent on the restraint configuration,

j. Since all restraints tested had design faults, it is concluded that no restraint can be completely eliminated as a potentially successful restraint mechanism.

Tools

a. Off-the-shelf adjustable wrenches should not be used for EVA assembly and erection.

b. Socket-type wrench sets, if used for EVA assembly and erection, will require modification to assure positive locking of the interchangeable connections.

c. Screwdriver use should be avoided for EVA erection, assembly, and maintenance tasks.

d. Tools performance improves with the improved stability of positioning.

e. When the subject was well positioned to the work spot and had a stable position, little difference could be noted in the variety of wrenches tested.

f. Pliers and pincher-type handles require modification to allow manipulation with one hand,

g. The simple flexible lanyard used in these tests for tool retention is inadequate.

h. Testing of all tools to be used during EVA in the neutral buoyance water immersion simulation is required to assure their adequacy.

i. Hammer blow accuracy is interfered with by suit resistance.

Fasteners

a. A need exists for a clamp that may be manipulated with one hand to position, adjust, engage, and release.

b. Off-the-shelf clamps are not acceptable for EVA assembly and erection.

c. A requirement exists to establish ways and means of handling, retaining, and controlling bolts, nuts, and fasteners that are not captive.

d. A positive, quick locking fastener with high holding capability is required for EVA assembly and erection.

e. The internal wrenching bolts were the most desirable bolts tested and the slotted head bolts the least desirable.

f. Bolts with head sizes of less than 1/2 in. and lengths of less than 1 in. are undesirable for EVA because of their handling difficulty.

g. Fasteners for EVA erection and assembly should be standardized and of a minimum number of sizes.

Locomotion Aids

a. Rigidity of locomotion aids is desirable,

b. Locomotion aids without protrusions are the most desirable to prevent the EVA worker fran snagging his suit or equipment.

Work

a. EVA erection and assembly tasks should have step by step procedures developed by a simulation technique using real hardware to prove the concept, develop procedures, and provide the training necessary to assure success of the mission in space.

b. In tasks where several tools are used there exists a problem of tool presentation and retention.

c. Two-handed tasks should be eliminated from EVA tasks whenever possible.

d. A direct frontal extension of the arm requires more effort and discomfort than does a "hooking" extension of the arm.

e. Deviation from check-list task procedures should be allowed only when the task sequence has been proven unworkable.

f. Each step of EVA assembly and erection should be planned, tested and set in a check-list task sequence for performance compliance.

g. The pressurized glove of the suit does not provide appropriate feedback from tools or hardware to the EVA worker. This fact requires the subject to see the work he performs.

h. Any requirement for the EVA worker to use two tools simultaneously should be eliminated.

i. Whenever possible, two-handed task requirements are often broken down by subject innovations into one-handed task elements,

j. Accessibility is a compound problem complicated by pressure suit limitations, restraint configuration used, vision, and task demand. Free volume space about the work spot is therefore not an acceptable definition of accessability for EVA work.

SECTION 6

QUANTITATIVE RESULTS

DISCUSSION

Because of the exploratory nature of the study, the principal results are those given in the preceding section. This treatment of the quantitative data is presented to indicate to the reader how an analysis of the data might be undertaken with data more suitable to systematic analytic evaluation.

Psychological performance data are acquired concerning two principal variables: correctness or adequacy of response and time to complete a response. This applies in ,paper-and-pencil tests, vehicle control tasks, machine operation, general problem solving, and, in this instance, work in a simulated weightless condition. The adequacy of a measure of performance is dependent on the choice of units of performance such as level of detail, type of event the experimenter selects to record the performance adequacy, and choice of blocks of performance to measure and make recommendations for further work.

Also, in this section some patterns emerge about the performance itself on the basis of the quantitative data. These will be brought out and listed as hypotheses inasmuch as the data do not justify outright conclusions.

Finally, this section will show how the preliminary task taxonomy, developed as a side effort in this study, can be used in interpreting the quantitative results.

PROPORTIONS OF SUCCESSFUL COMPLETIONS

A simple index of the difficulty of a task or the success of a work aid is the proportion of times that a task was completed successfully in the circumstances given. Table 6-1 gives proportion of successful completions for the same subject in performance of the maintenance tasks. Each cell in the table has a double entry, a ratio and a percentage. The ratio is provided to give the reader a clear idea of what is involved. It is, in a sense, questionable whether eight successes of eleven tries is as good a record as eleven successes out of fifteen tries. The denominators of the ratios differ because each ratio is based upon the number of "fair tries" in a test. In some cases, the subject omitted a task, or the subject's neutral buoyancy was inadequate, or the test director instructed the subject to skip a given step.

TABLE 6-1

RATIO AND PERCENTAGE OF TASKS COMPLETED BY SUBECT TO TASKS ATTEMPTED BY SUBJECT

Test Code	11XX		12XX		13XX		Composite by Work Aid	
	Ratio	%	Ratio	%	Ratio	%	Ratio	%
XX11	11/15	0.73	-----	----	8/11	0.23	19/26	0.731
XX22	-----	----	Deleted	----	6/7	0.86	6/7	0.857
XX33	11/12	0.92	Deleted	----	Deleted	----	11/12	0.917
XX44	13/15	0.87	15/16	0.94	14/14	1.00	42/45	0.933
XX55	14/15	0.93	16/16	1.00	14/14	1.00	44/45	0.978
XX36	-----	----	-----	----	12/14	0.86	12/14	0.857
Composite by Task & Sequence	49/57	0.860	31/32	0.969	54/60	0.900	134/149	0.899

The denominator of each fraction represents the number of tasks attempted by the subject. The numerator represents the number of tasks that were attempted and completed. A task was designated as not completed when the subject stated that he could not complete the task. The reasons for noncompletion ranged from tool inadequacies to subject fatigue. The blanks in the table are for tests not performed by the subject. Tests 1.1.2.2. and 1.2.1.1. were performed by a different subject who never achieved good neutral buoyancy. Test 1.3.3.6. was conducted at the request of the contract monitor. Test 1.1.3.6. and 1.2.3.6. were, therefore, never actually scheduled.

The table indicates that a better performance was made with the use of the birdcage and footstrap restraints than with any other restraint system. This indication is a result of the considerations of the number of tasks attempted with each restraint system. It should be recognized that one of the weaknesses of quantitative data from exploratory work is that the test crew has the option to drop tasks that seem too unreasonable to do. Thus, the more difficult restraints, such as the three leg rigid restraint, were not tested as much and, therefore, should not be compared with the other restraints on the basis of the numerical data.

The table also indicates that the lowest success in completion of tasks was with the easiest task sequence. This observation is most likely an artifact of the order in which the various task sequences were done using each restraint system. Figure 6-1 shows the proportion of successful task completions with each restraint system that was used more than once. The notable point is that in two of the three cases (foot restraint and birdcage system), the easy task was done first. Thus, the learning effect contaminates the task difficulty data. Because the emphasis in exploratory work is on breadth rather than depth of coverage, such contamination is an inevitable price to be paid in achieving exploratory studies' goals,

The overall records of the three modes of simulation used in the maintenance tasks are given in Table 6-2. The shirtsleeves tests showed perfect performance; the full gravity suited tests and the underwater tests showed less than perfect performance, and finally, the tests in the six-degrees-of-freedom simulator showed perfect performance, A weakness in the data demonstrated that the test planning for the six-degrees-of-freedom simulator took advantage of prior test results and set up a test that could be performed using that method of simulation. This approach was advantageous for breadth of coverage, but not for depth.

TIMES TO COMPLETE THE TASKS

A second possible measure of a task and the associated work aids is the time to complete that task when it can be completed. Because of the great number of tasks to be considered, some approach is needed for analyzing them. The data on times to perform tasks will be organized in accordance with the

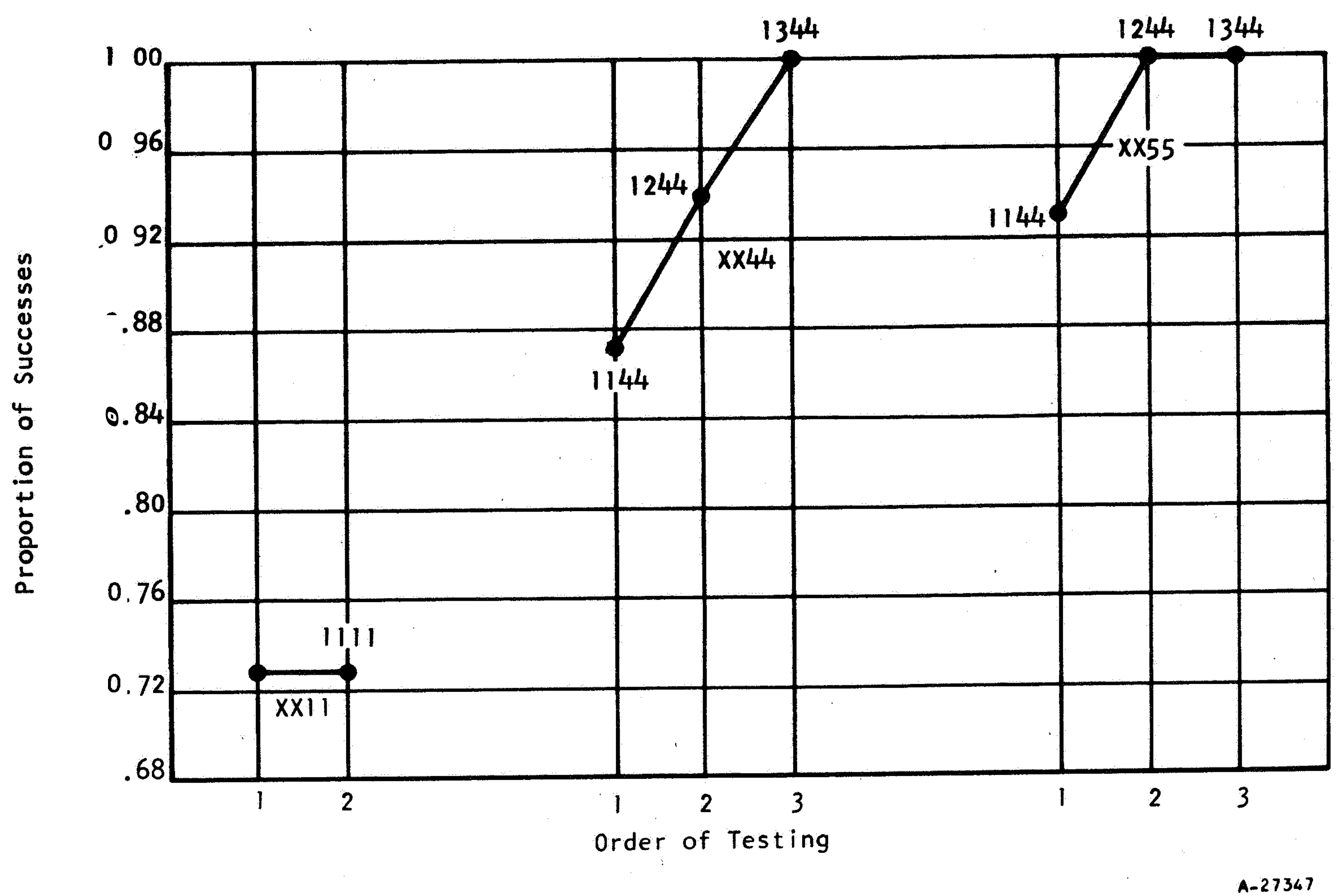


Figure 6-1. Relation of Task Completion and Restraint

TABLE 6-2

SUMMARY OF MAINTENANCE TASKS COMPLETED
TO MAINTENANCE TASKS ATTEMPTED

Description	11XX	12xx	13XX	3XXX
One-g shirtsleeve	68/68	46/46	56/56	
One-g suited pressurized	23/27	29/32	22/24	
Six-degrees-of-freedom, suited pressurized				21/21
Underwater suited pressurized	59/68	31/32	54/60	

NOTE: Like tests are indicated by tabular division above.

task taxonomy discussed in Section I of this report. It will be seen that the data are easily organized and understood in the light of the classification system.

DATA ON TASKS IN MOTION

Figure 6-2 shows the time data on the task of traversinq to the work station from the hatch, a distance of approximately 11 ft. It can be seen in Fiqure 6-2 that there is no pattern of improvement over time. Figure 6-3 shows a composite of the times for five different locomotion aids. These five graphs show the history for each locomotion aid. In the graphs, it can be seen that with each locomotion aid except one, later excursions were performed faster than earlier ones. Because data are so sparse, it is difficult to say whether the increase in time in the second traversal with the hand hold reflects on the locomotion aid. For this particular traversal, the subject stopped on the way, but the stop may or may not have been a direct result of the locomotion aid.

Prior to completing the examination of tasks in motion without a load, it is pertinent to review a task in motion with a load, such as traversing a somewhat shorter distance back to the hatch with the maintenance box attached to the shell. The time history of performing this task is given in Figure *6-4.* The second use of the bird cage restraint system in this series is outstandingly long. Otherwise, there is no indication of change in performance over time. Thus, the locomotion aids may be averaged meaningfully in both the case of motion with and without a load.

Figure 6-5 shows the performance times for traversal with and without loads. The rigid pole is common to both graphs and is among the best locomotion aids in both graphs. The interesting difference between the two graphs is that without a load, the hand hold (T-bar or ladder) locomotion aid and the rope tether (which in practice amounted to a hand hold locomotion aid due to the subject using the eye bolt restraint holders on the mock up to traverse instead of the rope) show no significant improvement over the taut rope as a locomotion aid. With a load, however, the rope tether and hand hold are at least as good as the rigid rope. With more data *to* substantiate the graph in Figure 6-5 than are currently available, it can be asserted that the presence of a load makes hand holds more useful as a locomotion aid.

The third type of motion that appears in the task taxonomy is motion while restrained. An example of this category is the task of putting the pipe, removed during the hard task, into the tool kit. Figure 6-6 shows the times used by the subject in completing this task. The best performance was accomplished using the birdcage restraint. The worst performance came with the use of the two-leg restraint, which is understandable when one considers that in using this restraint the subject had to detach and reattach the restraints as he moved toward the tool kit to put the pipe away.

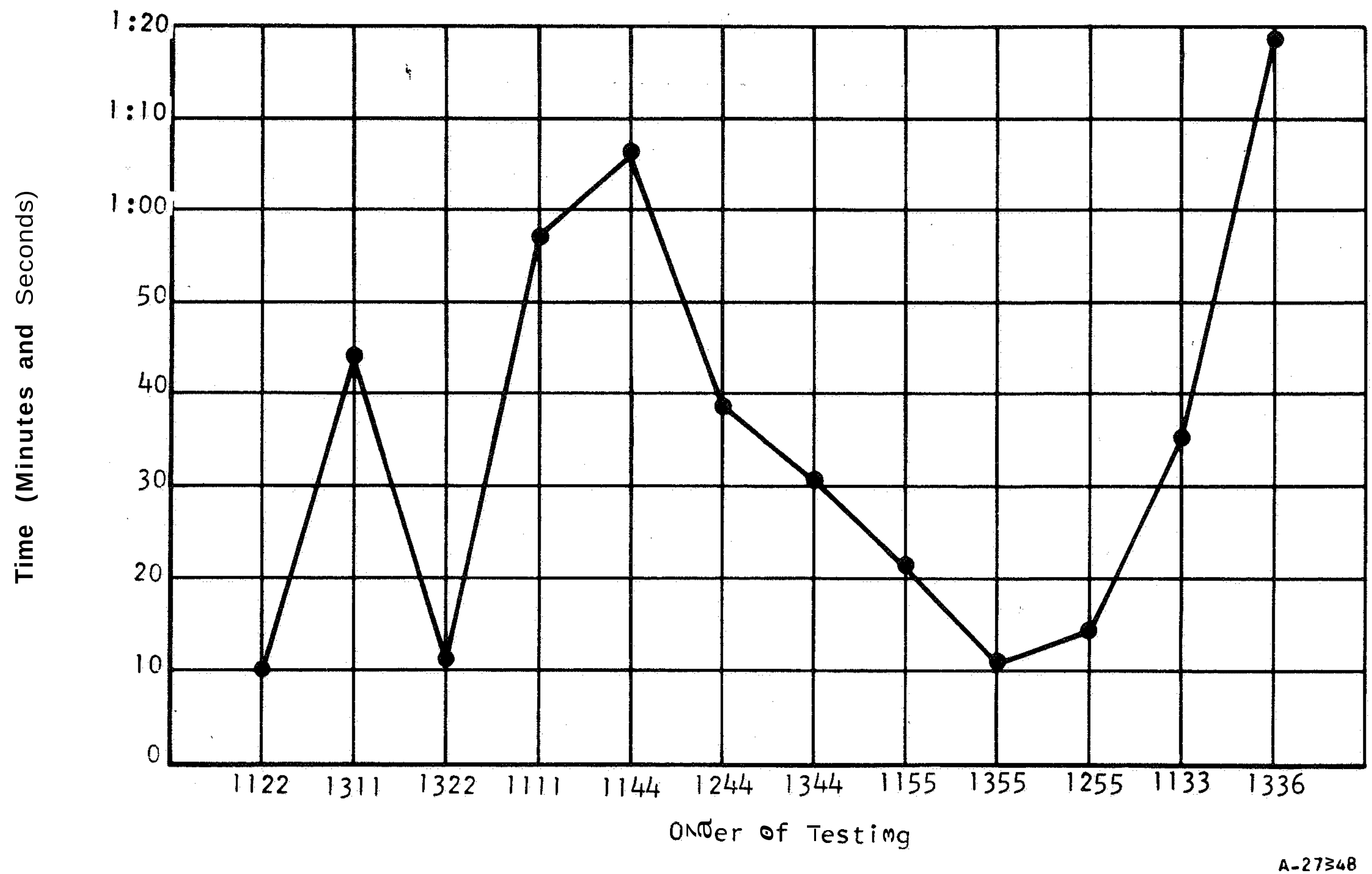


Figure 6-2. Time to Traverse to Work Station From First Test Performed to Last Test Performed

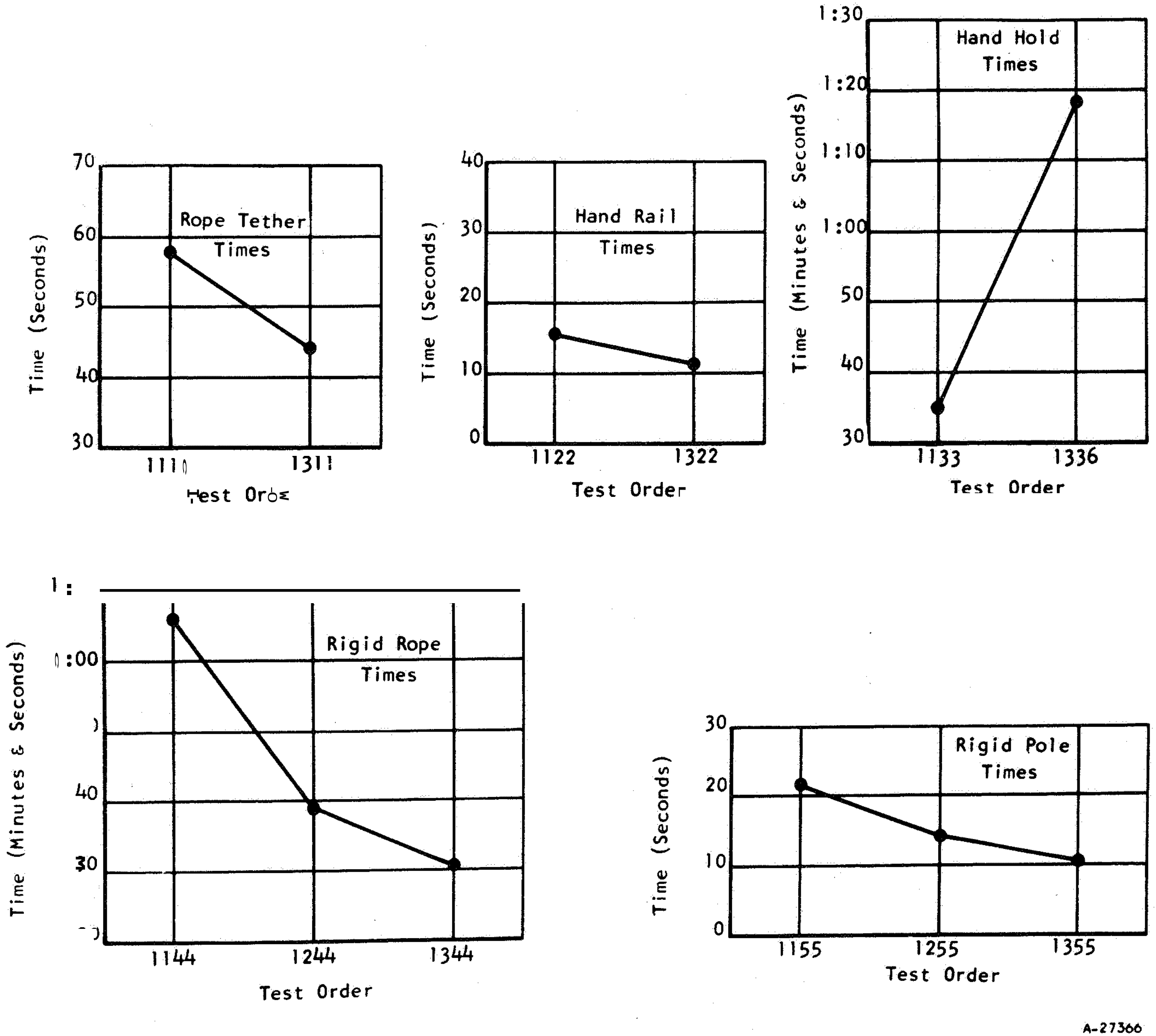


Figure 6-3. Subject Traversing From Spacecraft Mockup Hatch to Work Station

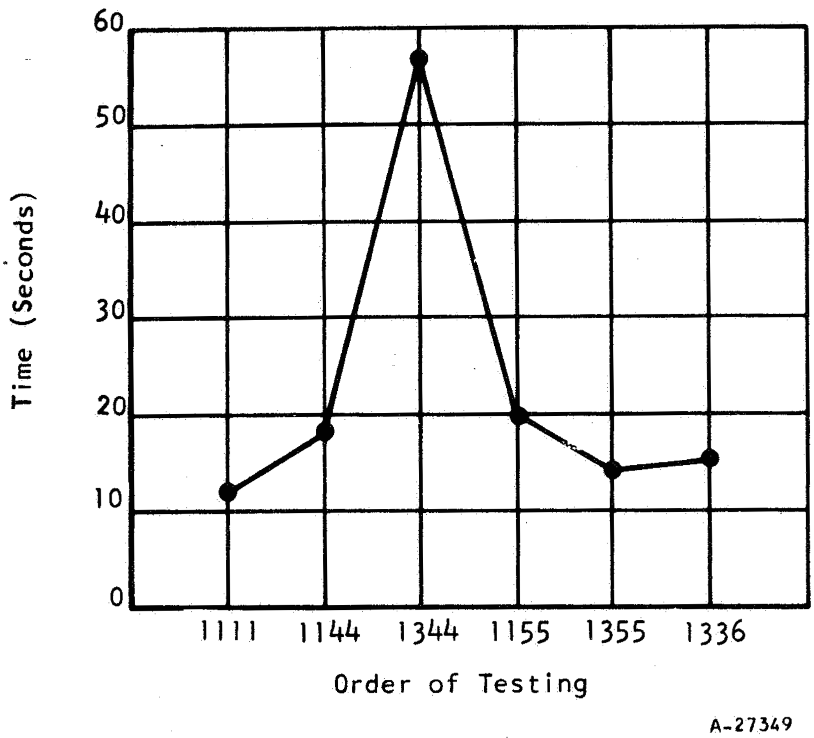


Figure 6-4. Times to Traverse to Hatch With Maintenance Box

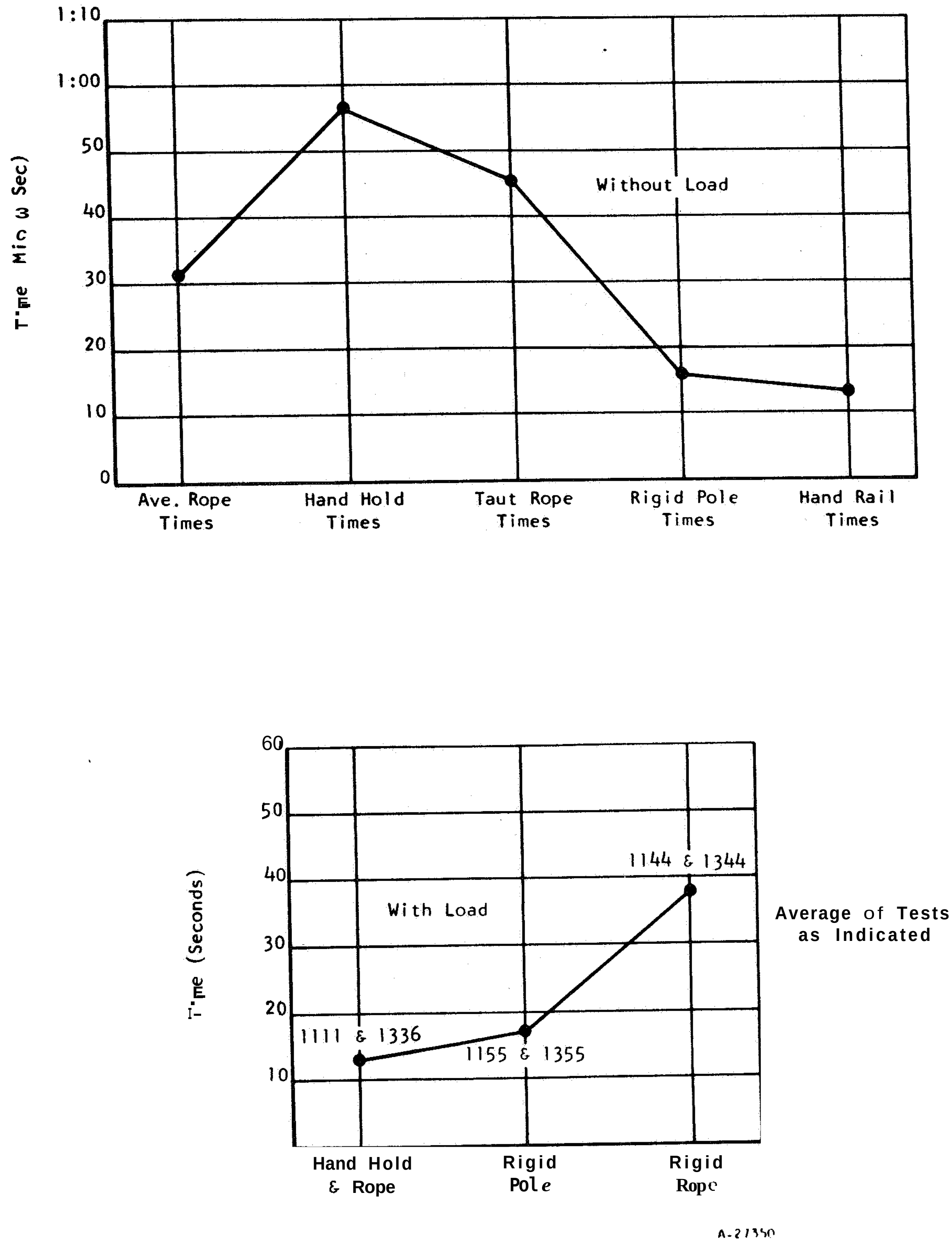


Figure 6-5. **Composite of Times for Locomotion Aids With and Without Load**

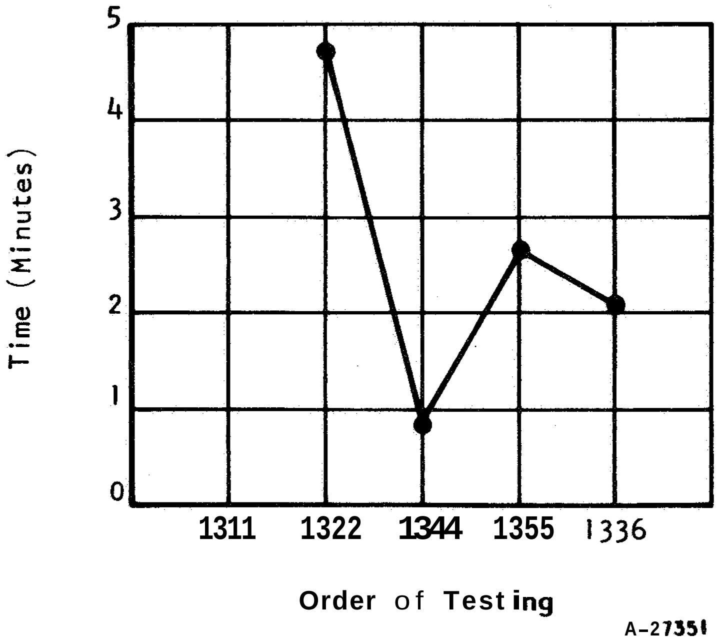


Figure 6-6. Completion Time for Subject to Put Pipe Segment in Tool Kit

It is difficult to apply the task taxonomy to the current data because the experiments were set up while the taxonomy was still embryonic. Many of the test activities that were timed include more than one category of activity. An example of this is the graph in Figure 6-7. The task here is a combination of fetching bolts from the tool kit and tightening them in the access panel, which has been put back over the access opening.

The birdcage does not compare as favorably as the single-leg rigid restraint. The question as to whether getting the bolts or tightening the bolts predominates in this situation is partially answered by the relationship between the two curves in the figure. The lower curve differs from the upper only with respect to the addition of a tool. It is practically parallel to the upper. It can tentatively be concluded from this figure and the preceding one that the birdcage is the best restraint for locomotion while restrained, but is inferior in the job of working with bolts. A parallel set of cases will arise later.

ASTRONAUT IS FREE AT HIS WORK STATION

This task category is not heavily represented in the maintenance tasks. An example that occurs throughout the maintenance tasks is that of attaching the restraint upon arriving at the work station. As seen in Figure 6-8, there is no clear pattern of learning in this task. Figure *6-9,* however, shows an interesting distinction between the learning patterns of four restraint systems. The rigid leg restraints, either one or two leg, took longer to use the second time than the first. The foot-strap and cage-strap systems, on the other hand, were systems in which the subject improved his ability. The need to learn how to enter a cage or get set up in a foot-strap system is easily understood. The reason for the increase in time to engage the other two restraints systems to the spacecraft mockup is not apparent and must go unexplained.

Figure 6-10 shows the various restraints compared in terms of mean attachment time. For this type of task, the birdcage and Gemini XII type of strap restraint systems took the longest. As mentioned in Section 5, these tests reflect results about the configuration used and do not necessarily fully evaluate the concepts. The difficulty with the Gemini XII type of strap restraint was that the subject had trouble finding the ends of the straps. A design improvement may be possible here. By far the quickest attachment can be made with the single rigid leg, which is somewhat easier to find and takes only one connection to complete the job.

TASKS RESTRAINED AND STATIONARY

As seen in the task taxonomy classification (Section I), the tasks that are performed with the subject restrained and station may or may not require the subject to reach or stretch to perform his work. Strictly speaking, this classification is interdependent with the restraint. For example, the subject will have to stretch farther to do a job 18 in. inside the access opening when

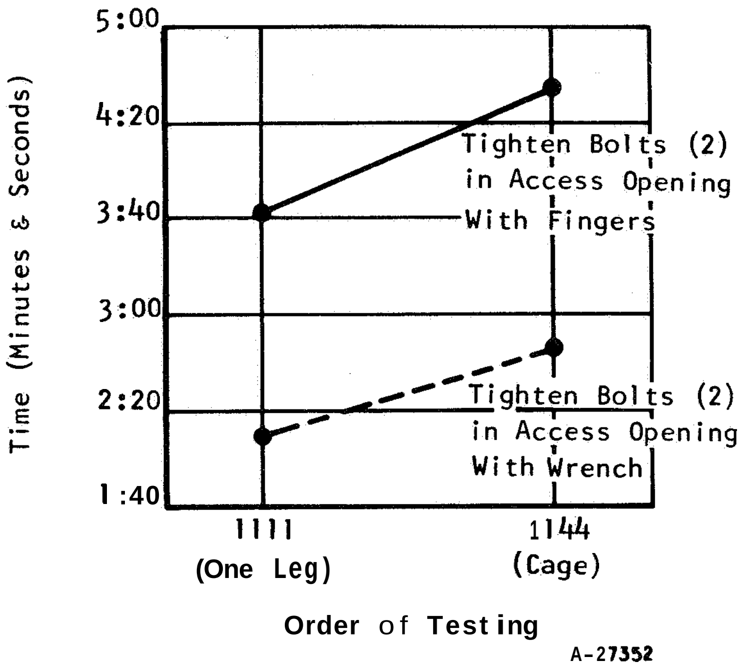


Figure 6-7. Example of Test Activity Covering More Than One Task Taxonomy Category

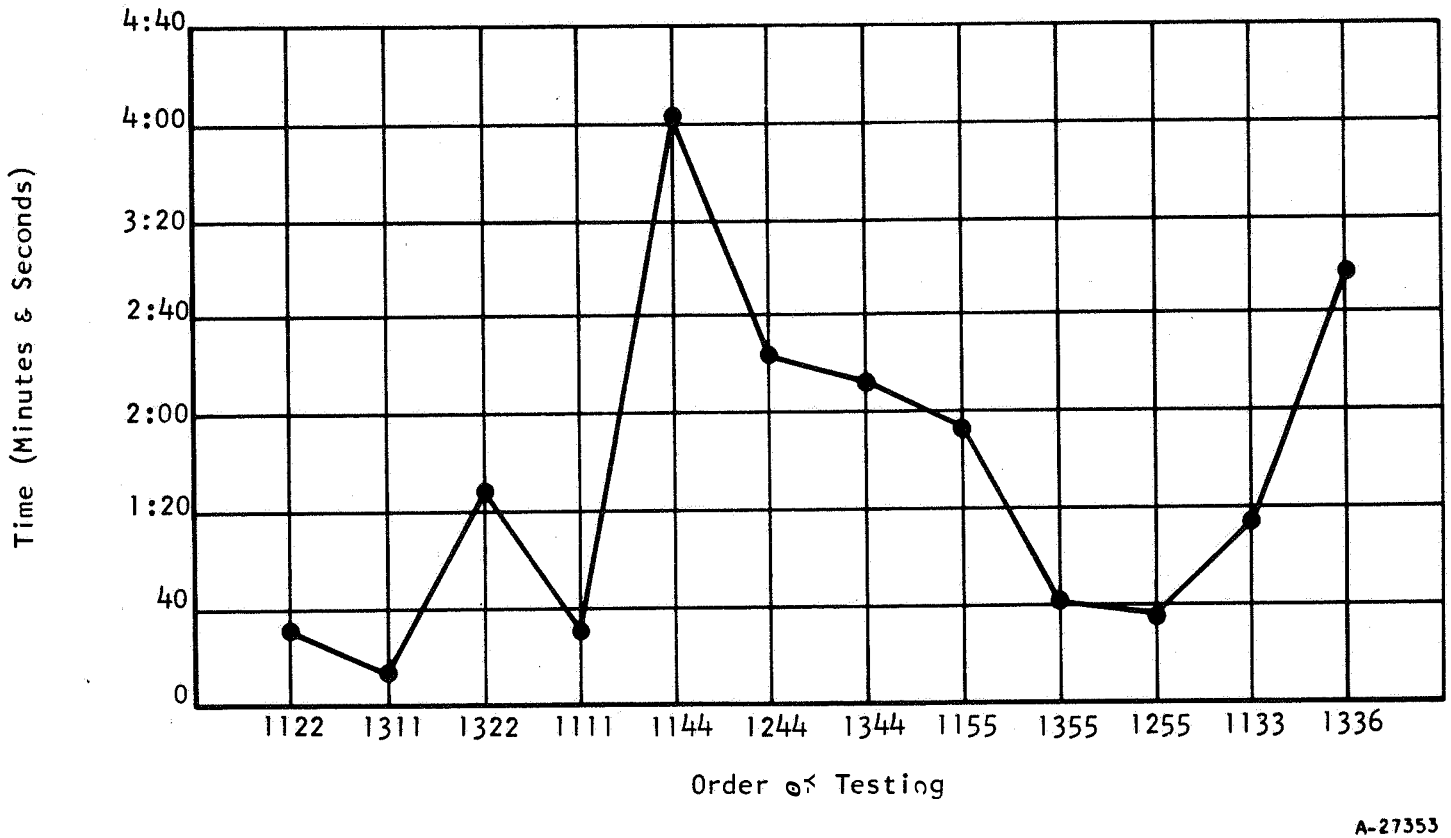


Figure 6-8. Completion Time for Engaging Restraint

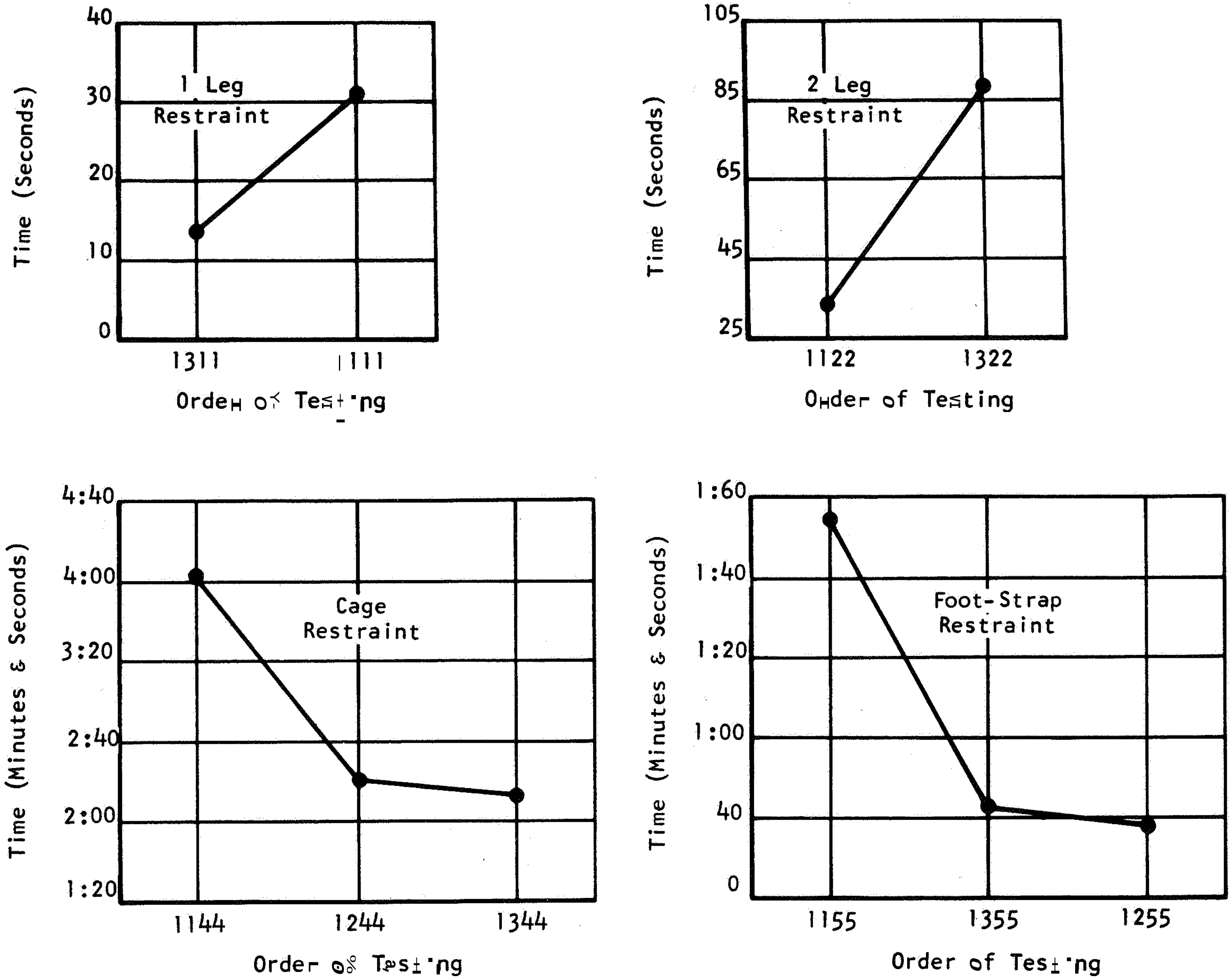


Figure 6-9. Completion Time for Engaging Restraint

A-27354

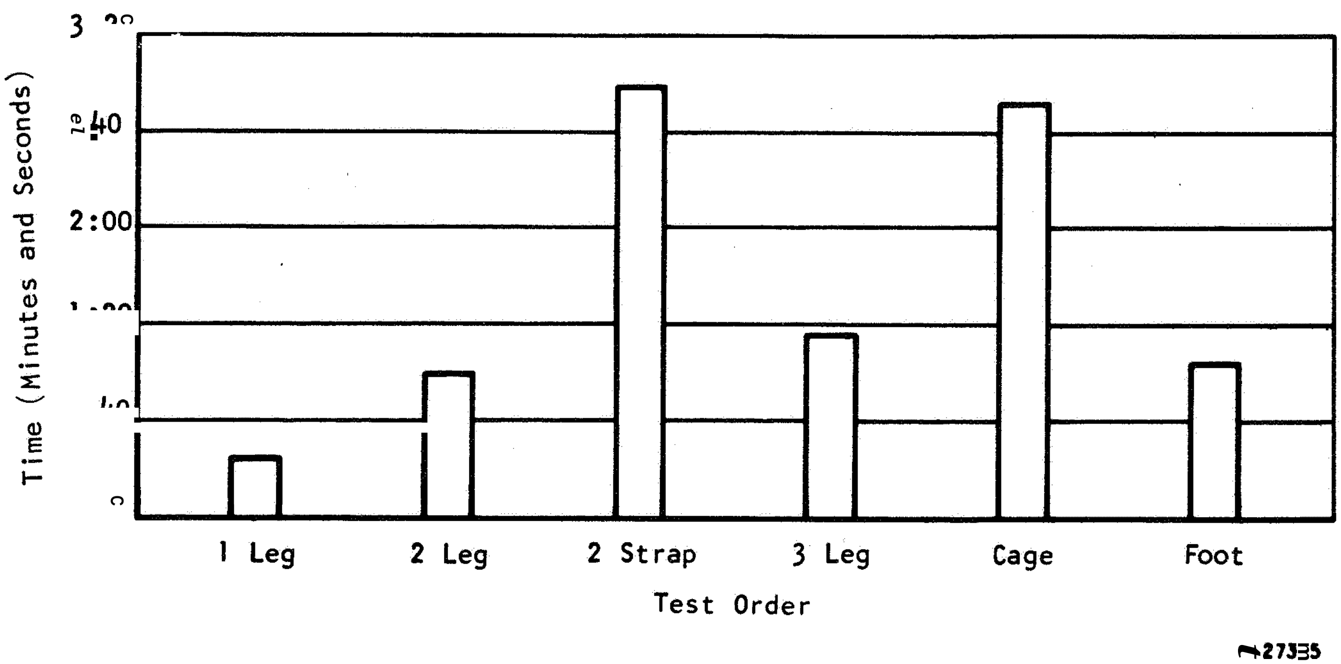


Figure 6-10 Average Completion Time to Engage Restraint

using the three rigid leg restraint than when he is using the cage restraint. The interdependence, as mentioned in the discussion of the taxonomy, is a problem to be worked in future revisions of the taxonomy.

Figure 6-11 shows the performance of two different tasks in the order in which they were performed. In both tasks the relative times associated with each restraint are the same. The restraints are used in the same order in both cases. The two tasks are in the same category of the task taxonomy in general, but according to the force and dexterity requirements, they would ultimately be placed in different categories. Moving the wires was a job that could vary from 3 to 9 min (this task involved manipulating the fasteners that held the wires down). This was a slow job requiring high dexterity. Cutting the bolt was a fast job requiring force. In both tasks the completion time when using the foot-strap restraint was faster than when using either the birdcage or the Gemini XII type of strap restraints. The flexible strap restraint is more clearly inferior inasmuch as additional time was required to perform the task even though the task occurred later in time and should have reflected some learning.

Figure 6-12 shows a different task in which performance times using the birdcage and three rigid leg restraint configurations are less than that of the foot-strap ,restraint configuration. Cutting the wires to the maintenance box involves tool manipulation, as do the other two. The dexterity requirement is not as great as that for moving wires and the force requirement is not as great as that for cutting the bolt. The key to this task is getting into position quickly and getting the wires cut. It requires freedom of movement in a close area. In this task the foot-strap restraint does not show the advantage that it showed for tasks requiring force or finer dexterity.

The data in Figures 6-11 and 6-12 (even if there were enough data and they were statistically significant) cannot be taken to mean that the foot-strap restraint is superior whenever great force is required in the performance of a task. Another important variable is the direction of the force. Figure 6-13 shows three tasks requiring force in which the performance times consistently decrease on each successive attempt. This is in contrast to the instances in Figure 6-11, in which the Gemini XII type of strap restraint did not work as well as the foot-strap restraint. The general form of a learning curve for time data consists of each successive gain in performance time being less than the last gain. Only one case in Figure 6-13 shows the Gemini XII type of strap restraint having less gain over the foot-strap restraint than the foot-strap restraint showed over the birdcage. This is the task of sawing the bar. The task of filing the notch in the bar before sawing shows a greater gain for the Gemini XII type of strap restraint than might be expected. The gain is most dramatic in the case of disengaging the pipe. This is the two-wrench task, which required more force than any other single task. In all of these tasks,

3

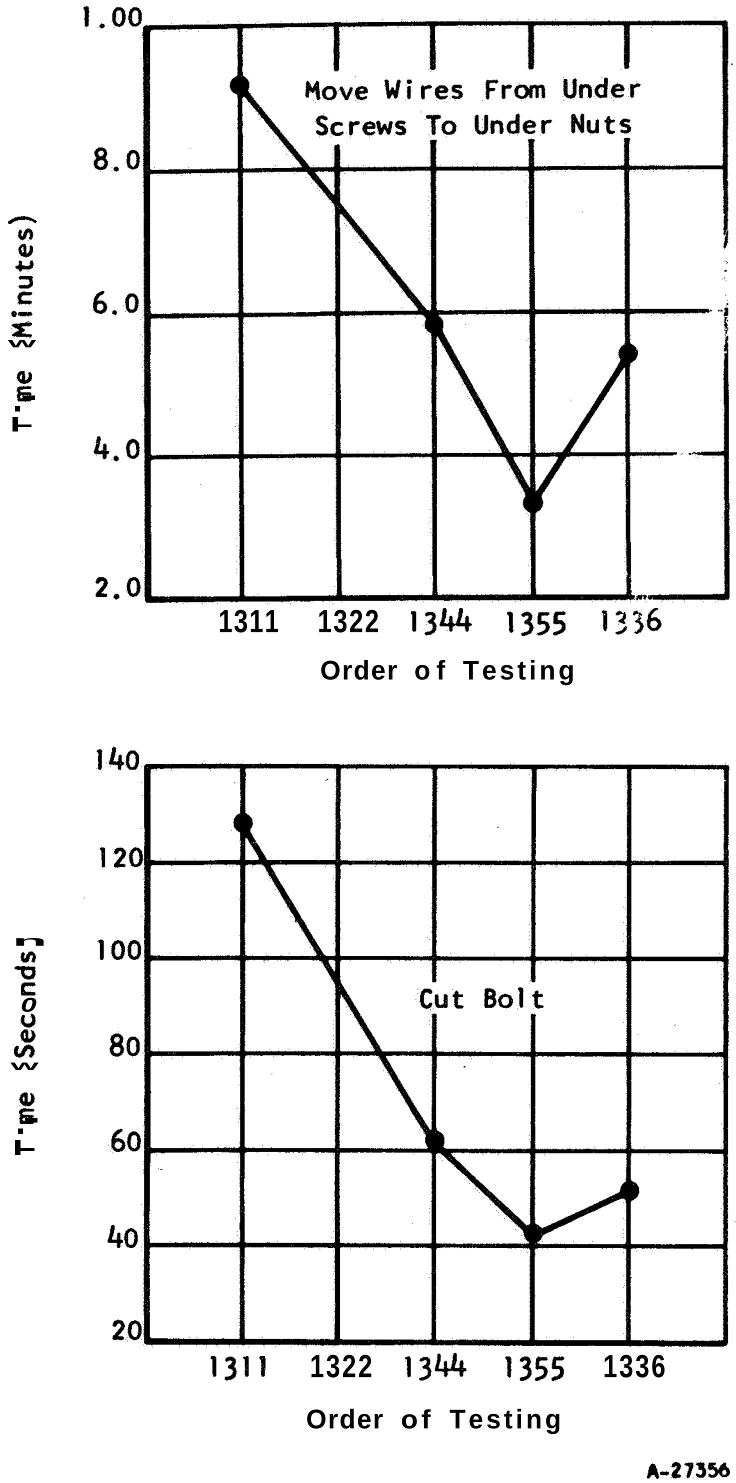


Figure 6-11. Task Completion Time for a Task Requiring Dexterity and a Task Requiring Force

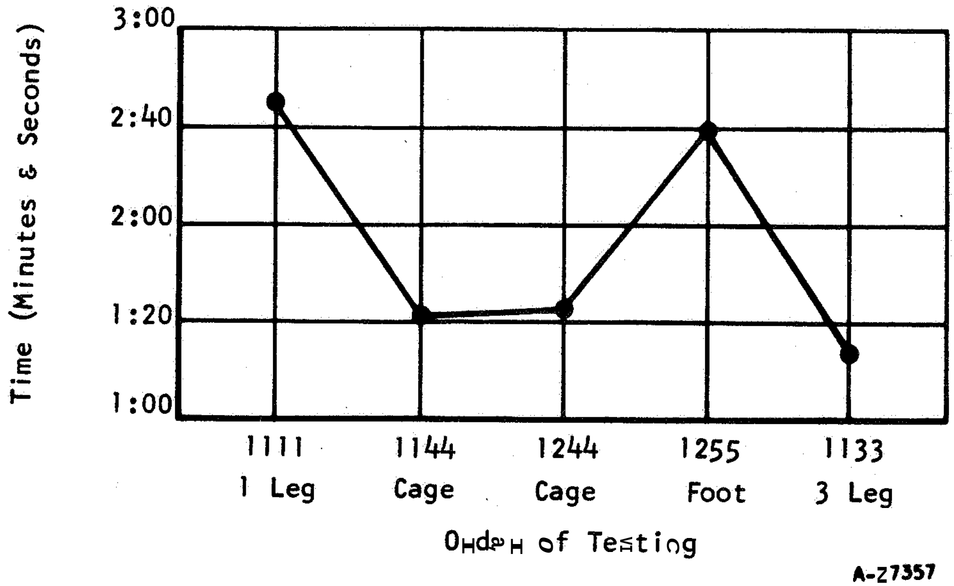


Figure 6-12. Task Performance Time for Cutting the Wires to the Maintenance Box

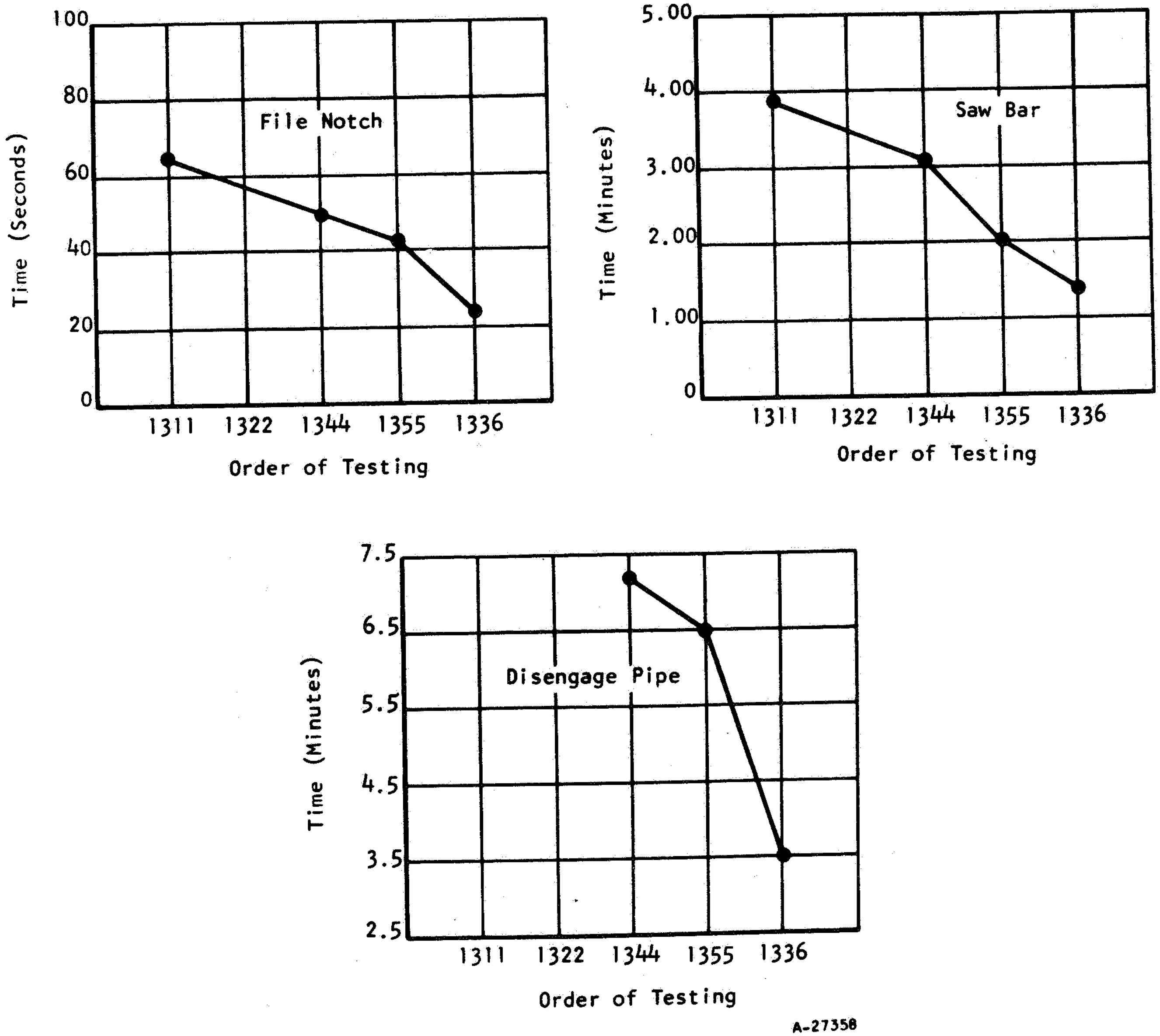


Figure 6-13. Performance Improvement With Practice

shown in Figure *6-13,* the Gemini XII type of strap restraint is at least as good as the foot-strap restraint. In at least one case, the Gemini XII type of strap restraint is clearly better. The difference between the data in Figure *6-13* and the second graph in Figure 6-11 is the direction of force. When the force is applied so as to oppose the restraint, the Gemini XII type of strap restraint works very well. This permits the assumption of the lineman's position in its best form. When the force is applied in a direction irrelevant to the restraint, as with the bolt cutters, the tool grasped (bolt cutters in this case) becomes a restraint for a brief moment and the hold of the restraint system can be broken. As seen in Figure 6-11, the foot-strap restraint is least vulnerable to this sudden shift of base with the possible consequence of breaking the position.

Because it was introduced late in the series of exploratory tests, the Gemini XII type of strap restraint was not compared with the other restraints in many applications. The observations about its outstanding performance in tasks requiring great force which oppose the restraint and its relative lack of merit when dexterity is required or a different force is exerted are the sole observations that can be made from the quantitative data.

Because the restraint devices and tools both were changed from task to task, it is difficult to sort out the differences between performances as attributable to restraint or tool. Figure *6-14* shows a comparison that can reasonably be related to differences between tools. In Figure *6-14,* the data are shown for three tasks in which the subject had to reach and stretch to the same point in the maintenance mockup. The task related to a tube which came from the top of the maintenance box to the side of the mockup. In the first task, the subject's job was to disengage the tube using two wrenches, in the second with one wrench, and in the third the subject was to turn off a valve on the tube line. Doing the job with two wrenches usinq the birdcage restraint system and a hook and crescent wrench took 50 percent longer than using two open-end wrenches and the foot-strap restraint. In the one wrench task the foot-strap restraint with a crescent wrench did not look as good as the combination of the birdcage and an open-end wrench. Finally, it is notable that when no tools were involved, the two restraint systems gave virtually identical times on both the first and second attempt. On the basis of the result with no tool it is reasonable to suppose that the difference may be attributable to the type of tool used. The short time performance in the first two graphs in Figure *6-14* is associated with open-end wrenches, while the longer performance time is associated with a crescent wrench. Thus, the three graphs in Figure 6-14, taken together, lead to the hypothesis that an open end wrench is superior in this task to a crescent wrench.

The final task category to be considered is that of working in place, reaching, and stretching with a load. Figure 6-15 shows a contrast involving loads reminiscent of that concerned with motion in connection with Figures 6-6 and 6-7. In the first graph, there are two tasks for which the data are drawn. Both tasks involve moving a load and starting to secure

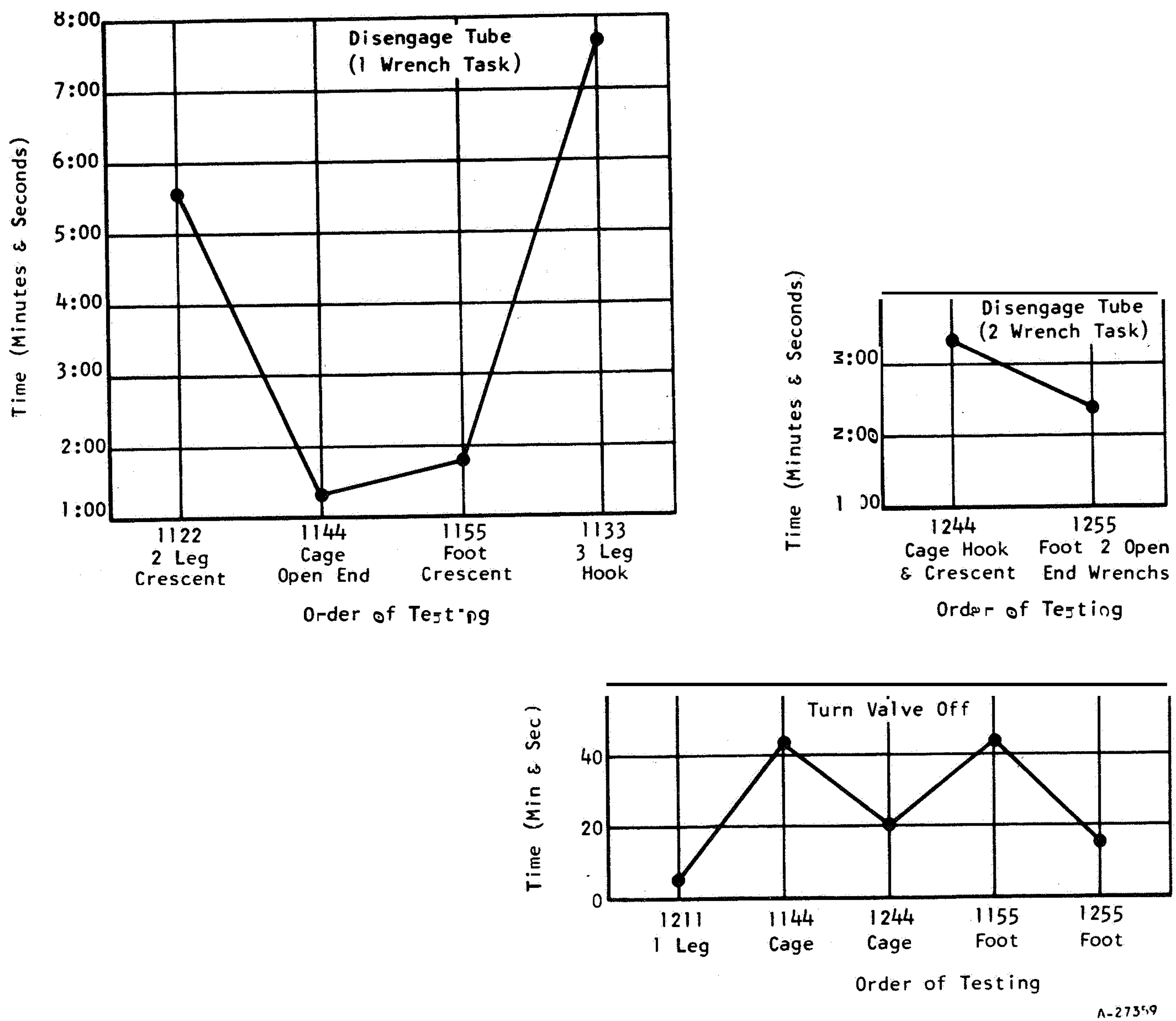


Figure 6-14 Completion Time Differences as a Function of Tool Type Used in Task

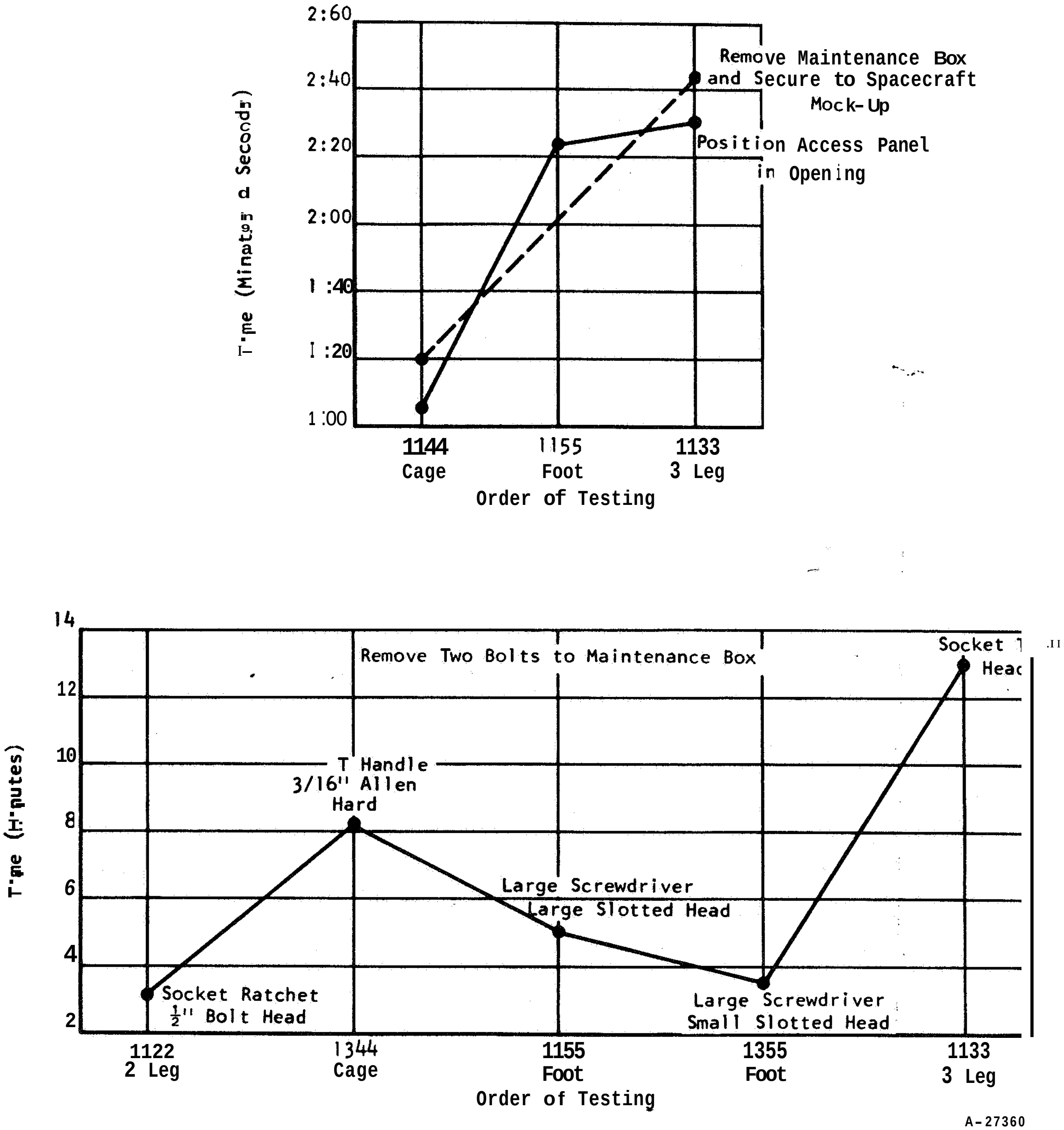


Figure 6-15. Tasks Involving Moving a Load and Starting to Secure It to the Parent Mass

it to the parent mass. For both tasks, the cage restraint, which was used first, takes less time than the three rigid legs; and for removing the maintenance box, the cage restraint takes less time than the foot-strap restraint. This is similar to the case of being in restrained motion with a load. Also in Figure 6-15 is a graph of the changeover time in the performance of a task involving reaching and stretching, partly with a load and partly working with tools to remove tow bolts. The birdcage restraint system leads to a slow performance, while the foot-strap restraint leads to a speedy performance. As in Figure 6-7, a rigid leg restraint is superior to the birdcage. The restraint in Figure 6-7 was a one-leg device; in this case it is a two-leg restraint. Again, the job of loosening bolts overrides the aspects of the task concerned with flexibility of motion and of stretching.

It would be tempting to conclude that the birdcage restraint system is the best system tested so far for tasks in motion or involving stretching. Strictly speaking the numerical data of the study are too sparse and unreliable for that conclusion. There is also the problem of contamination among variables. Figure 6-16 illustrates a problem in which the mutual interactions of learning, the restraint device and the tool used make it impossible to attribute the differences seen in the graph to one variable. As seen in the figure, there is a general tendency for times to decrease in successive attempts to do the job. The birdcage system is used early in practice, so it appears inferior on that account. Also, the C-clamp is a most unwieldly tool for weightless work; the C-clamp represents a nearly unworkable limit in clamps. The subject has to use two hands to operate the clamp or else try to control the size of the opening of the clamp's jaws by grasping the threaded handle and swinging the rest of the clamp around, using these threads as a rotational axis. The type of data represented in Figure 6-16 makes it difficult, if not impossible, to sort out of the effects of learning, tools, restraints and other associated factors. Most of the data collected in the study were of this sort. The data represented in Figures 6-2 through 6-15 provide more opportunity to draw conclusions for a variety of reasons. Some categories were repeated in relatively pure comparisons. Some comparisons were based on a systematic change in one dimension along with other changes presumed to make little difference. Some comparisons occurred repeatedly in different circumstances but pointed to the same result.

An example of the value of cross-comparison in sorting out sources of differences was given in connection with Figures 6-6, 6-7, and 6-15. In this set of graphs, the observation was made that the bird cage restraint is associated with speed of task performance in tasks requiring restrained motion of reaching and stretching, unless the job of tightening bolts entered into the task. Figure 6-17 gives more information on this general area. The task represented is that of removing all four bolts from the access panel before the subject starts work inside the maintenance mockup (The reason only five tests are represented is that the number of bolts the subject was required to remove was unsystematically varied from four to two to none.

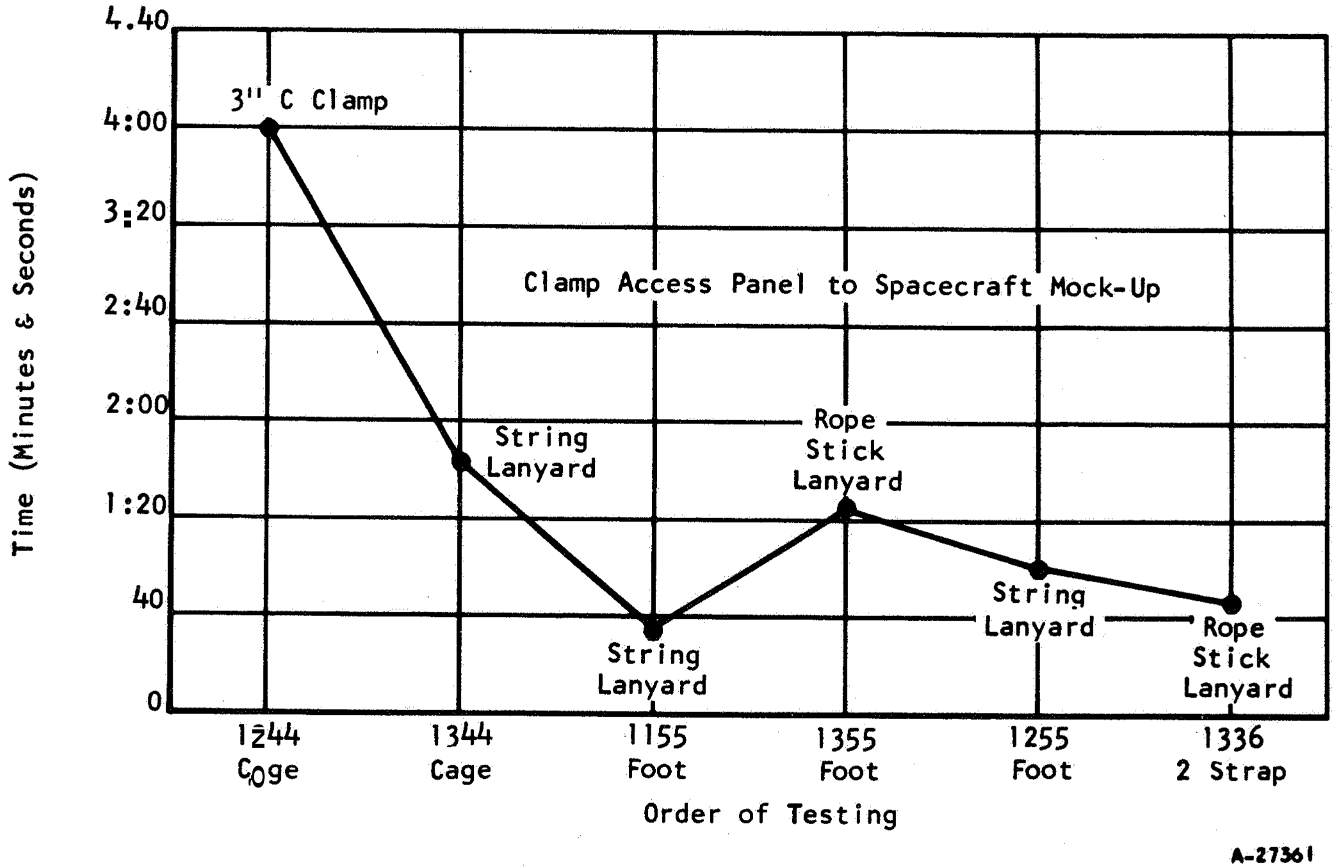


Figure 6-16. Task Illustrating Contamination of Variables

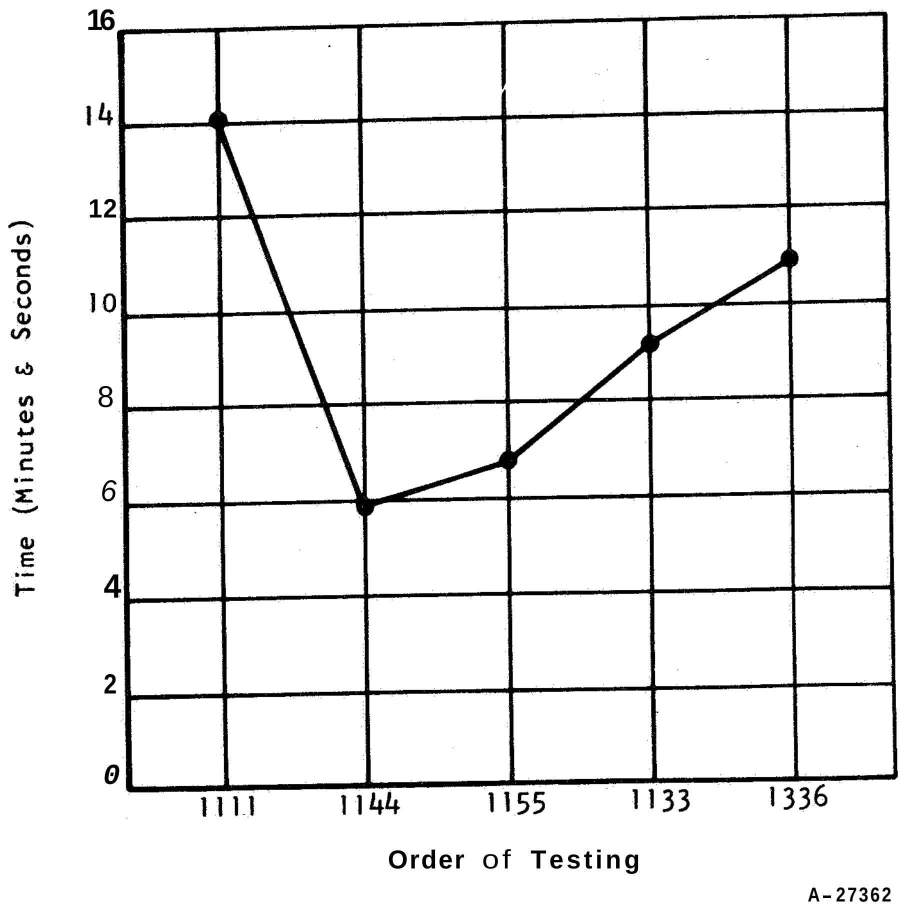


Figure 6–17. Completion Times for Removing Four Bolts to Access Panel

This was done at the direction of the human engineering observer and test director to facilitate arriving at the observations of qualitative performance mechanisms, which are reported in the preceding part of this section.) In Figure **6-17** it can be seen that learning is not a great factor in determining how long it took to remove the four bolts in the panel. Learning may well explain the difference in times between performance on Task IIII, using a single leg restraint, and Task **1133,** in which a three-leg restraint was used. But learning will not explain why the birdcage restraint led to the best performance time. Comparing this result to the contrasting result in Figure **6-8** and the second graph in Figure **6-16** leads to the observation that when two bolts and short distances for reach are involved, the birdcage does not compare exceptionally well. But when four bolts are spread over a larger distance, then the factors of motion, reach, and ease of finding position enter in and the birdcage restraint looks best. The questions as to how much distance, what kind of bolts and what kind of tool, etc., point to the need for additional study that will concentrate on task elements such as simple reach, removing one bolt, and so forth. It should also be pointed out that before exploratory tests of the kind reported here were completed, such a systematic study would have been premature. It was necessary first to get into the test situation to get an idea of the mechanism of keeping in place in a simulated environment and the general problems of getting work done under the test conditions.

USE OF THE QUANTITATIVE DATA IN PLANNING

The numerical data collected cannot be considered a final basis for conclusions on how a program or "in space" maintenance should be planned. It is possible, however, to make some use of the data until more dependable figures are obtained. Figures **6-18** and **6-19** show the performance times for two fragments of tests. In Figure **6-18,** the test from which the section is taken, is the so-called "difficult test," the one requiring more dexterity than the basic easy test. It is notable for this sequence of tasks that the foot-strap restraint is generally associated with a shorter performance time than the birdcage restraint. This sequence involves a number of tasks requiring stable positioning for one or two minutes while the subject concentrates on the action of his gloved hands. If a decision had to be made quickly on which type of restraint system to use for this type of sequence, the foot-strap restraint would be chosen. It should be noted that the choice of restraint for a task sequence will be improved by the following.

a. Tests on improved configurations of the restraint concepts

b. More intensive study of certain restraints and tasks with several subjects

c. A useful task taxonomy which would relate the tasks on which the tests were conducted to those to be done in space in a manner that makes it possible to generalize results

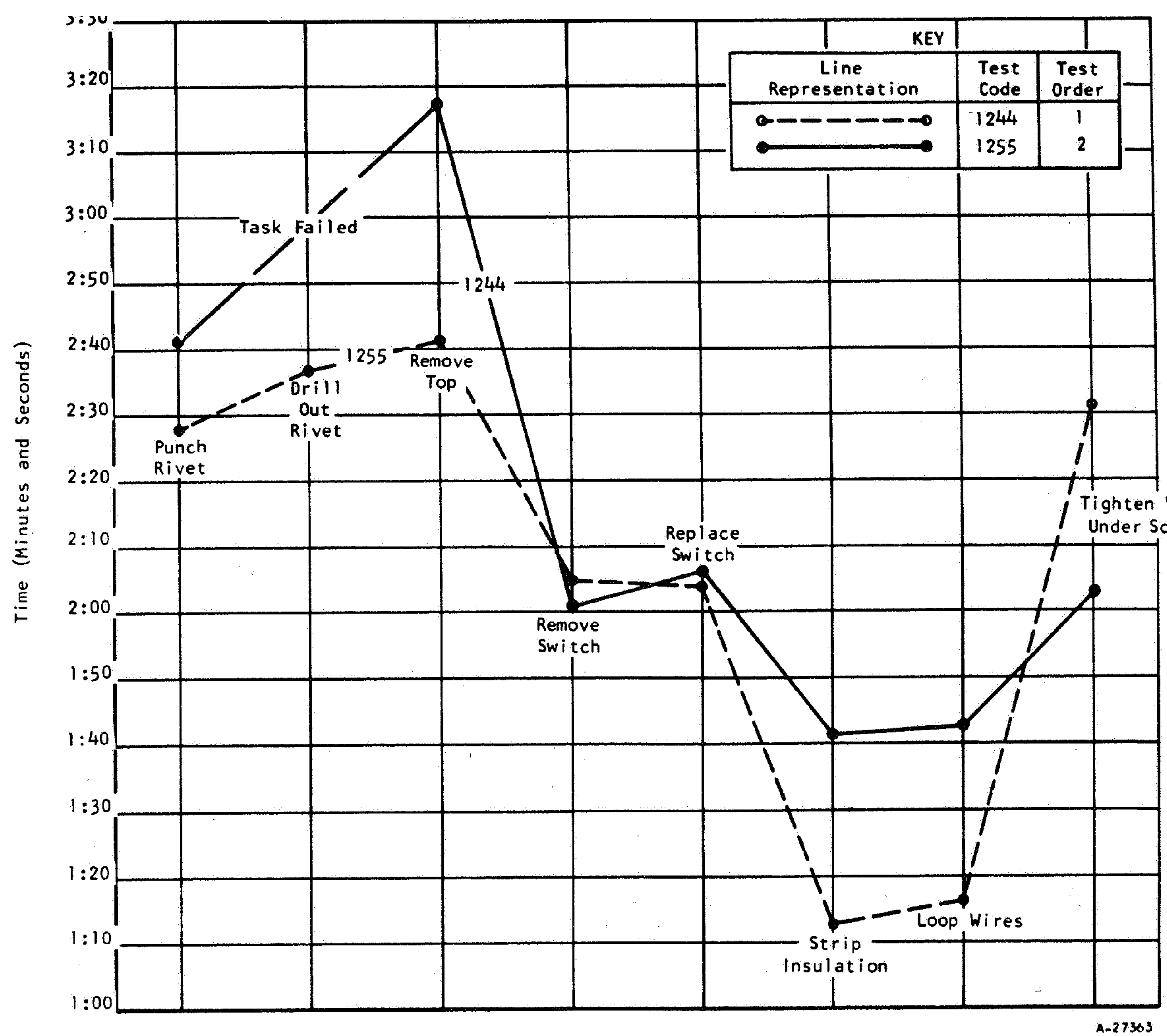


Figure 6-18 Partial Comparison of Performance Times of Two Difficult Maintenance Tests

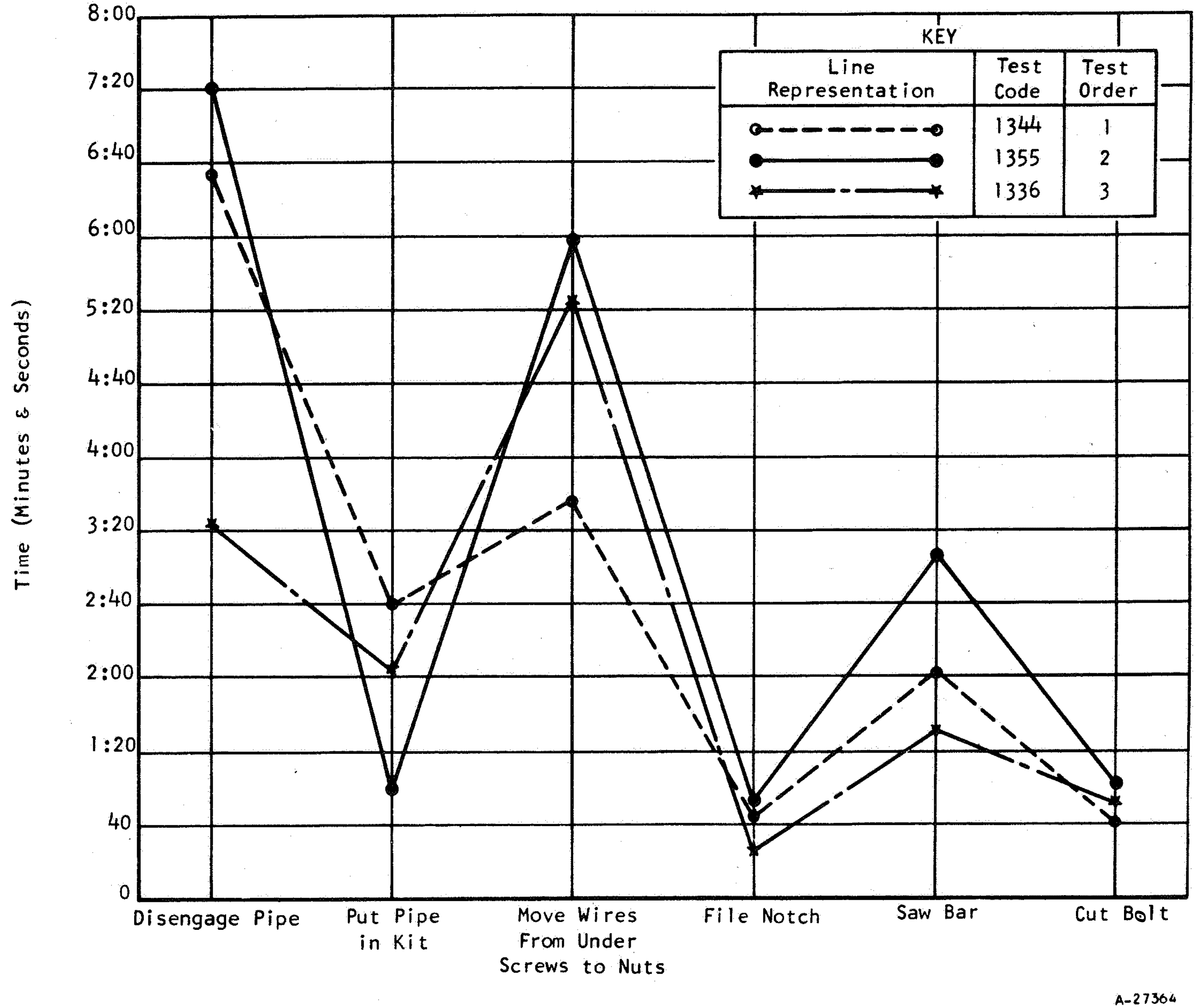


Figure 6-19. Partial Comparison of Performance Times of Three Hard Maintenance Tests

Figure 6-19 shows the performance times using three different restraint systems of a sequence from the hard task series, the job for which the subject was required to exert force. Most of these jobs have been seen before in this chapter. Note that no restraint predominates as best. The birdcage is best for putting away the pipe; the Gemini XII type of strap restraint is best for jobs involving force in opposition to the straps, such as disengaging the pipe. The foot-strap restraint appears best for jobs requiring prolonged dexterity work and the ,job of cutting the bolt, which requires the exertion of force in a different direction from the tension exerted by the subject against the mock-up. This last example, cutting the bolt, leads to a new point on the use of quantitative data in planning. The difference involved with cutting the bolt, though systematic as explained earlier in this chapter, is not great. It does not have as much impact on total performance time as the difference in disengaging the pipe.

Such a consideration leads to the plotting of a graph such as that in Figure 6-20, in which the various maintenance tasks studied are rank ordered according to the time consumed in performing them. As indicated previously, the task of disengaging the pipe unions is to the left on the graph, representing a high mean time, and that of cutting the bolt is near the right, representing a low mean time. With the use of information such as that portrayed in Figure 6-20, the decision would be to use the Gemini XII type of strap restraint. In this case it would be even more important than in the last case to have information on improved versions of the restraints involved, a more intensive study of certain restraints and tasks, and a useful task taxonomy.

The data plotted in Figure 6-20 provide the basis for still another type of planning decision. In a development program decisions have to be made on where to put the greatest research emphasis. One guide would be the potential saving in time to perform the tasks that could result from a development program. This would in turn mean that those tasks which take a long time would be the more likely tasks in which improvement could be made by a study effort.

It is notable that the three longest tasks involve fasteners and that the tasks ranked fifth and eighth involve fasteners, while fasteners are not involved in those tasks on the low time consumption end of the continuum. On the basis of his observations, the human engineering observer concluded that the chief hardware development problem in weightless maintenance is fasteners. These data support that view.

In Table 6-1 it was indicated that there were 15 tasks "fairly" attempted by the subject whose data are represented in that table, which he could not complete. These 15 tasks are broken down as follows:

Tasks Involving fasteners:	6
Tasks involving clamps:	4
Disengaging pipe unions:	3
Releasing and positioning the hatch panel:	1
Drilling out a rivet:	1

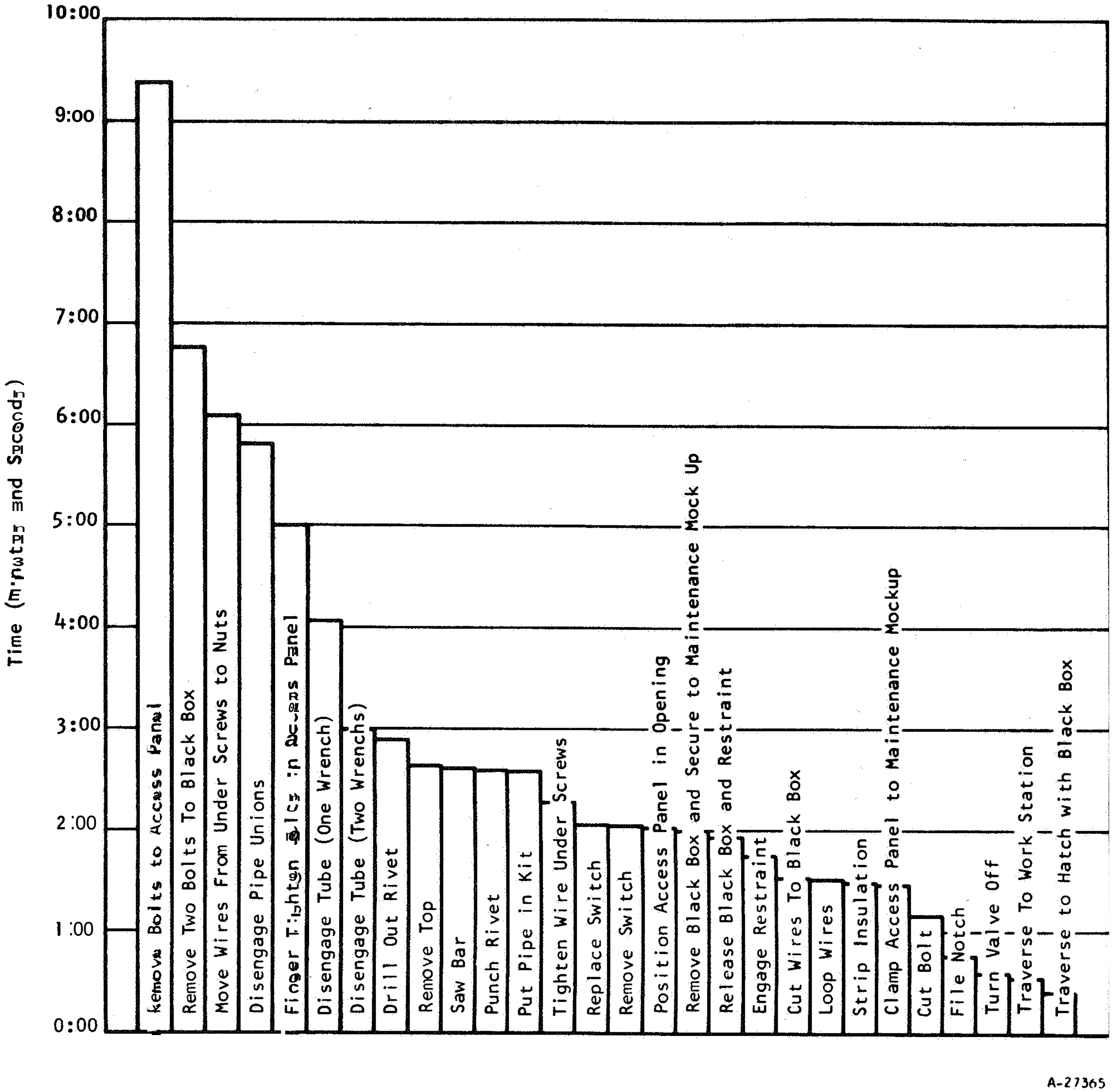


Figure 6-20. Mean Maintenance Task Completion Time, Longest Task to Shortest Task

It is notable that the tasks involving fasteners lead to more failures than other tasks. This result is hard to interpret because of the fact that tasks were not tried under uniform conditions at all times and because the failures involving fasteners are not given as a proportion of number of attempts to work with fasteners. Though such a computation can easily be made, it is best deferred until later work under more controlled conditions.

COMPARISON OF SIMULATION MODES

The completion times for five tasks of the hard maintenance test series performed in underwater zero-g simulation, in suspension zero-g simulation, and at one-g are presented in Figures 6-21 and 6-22. The only restraint used in the zero-g suspension simulation was the Gemini XII type of strap restraint. This restraint mode had to be used for comparing the underwater times with the suspension times. The strap restraint was not tested in the one-g tests. Comparisons were made of the one-leg restraint tests conducted at one-g and underwater and hypotheses drawn as to the differences between the suspension simulation and one-g conditions from the respective comparisons to the underwater simulation tests. Direct comparison cannot be made due to the lack of an orthogonal experimental design. Consequently, the hypotheses drawn from the one-g tests in relation to the suspension tests must be regarded lightly.

The length of time necessary to perform the five tasks for the unsuited one-g, suited one-g, and suited underwater conditions are presented in Figure 6-21. Task completion times for the suited one-g and suited underwater tests were greater than those for the unsuited one-g test in all cases. Task completion times for the suited underwater test were greater than those for the unsuited one-g test in all cases. Task completion times for the suited underwater test were greater than those for the suited one-g test in all cases except filing a notch in the bar. It was mentioned earlier that a decrease in completion time occurred with increased practice. Since the task was performed at one-g before it was performed underwater, the shorter time needed to complete this particular underwater task may be due to increased practice. Figure 6-22 shows that performance times for the five tasks were greater in all cases during suspension simulation then during underwater simulation.

From the aforementioned, the following can be hypothesized.

a. Task performnace is the quickest when the man is unsuited and working at one-g.

b. Task performance is quicker for a man working in a pressure suit at one-g than for a man in a pressure suit in an underwater, zero-g simulated conditions.

c. Task performance is slower for a man working in a pressure suit in the zero-g suspension simulator.

d. Task performance is shorter for a man working in a pressure suit at one-g than for a man working in a pressure suit in the zero-g suspension simulator.

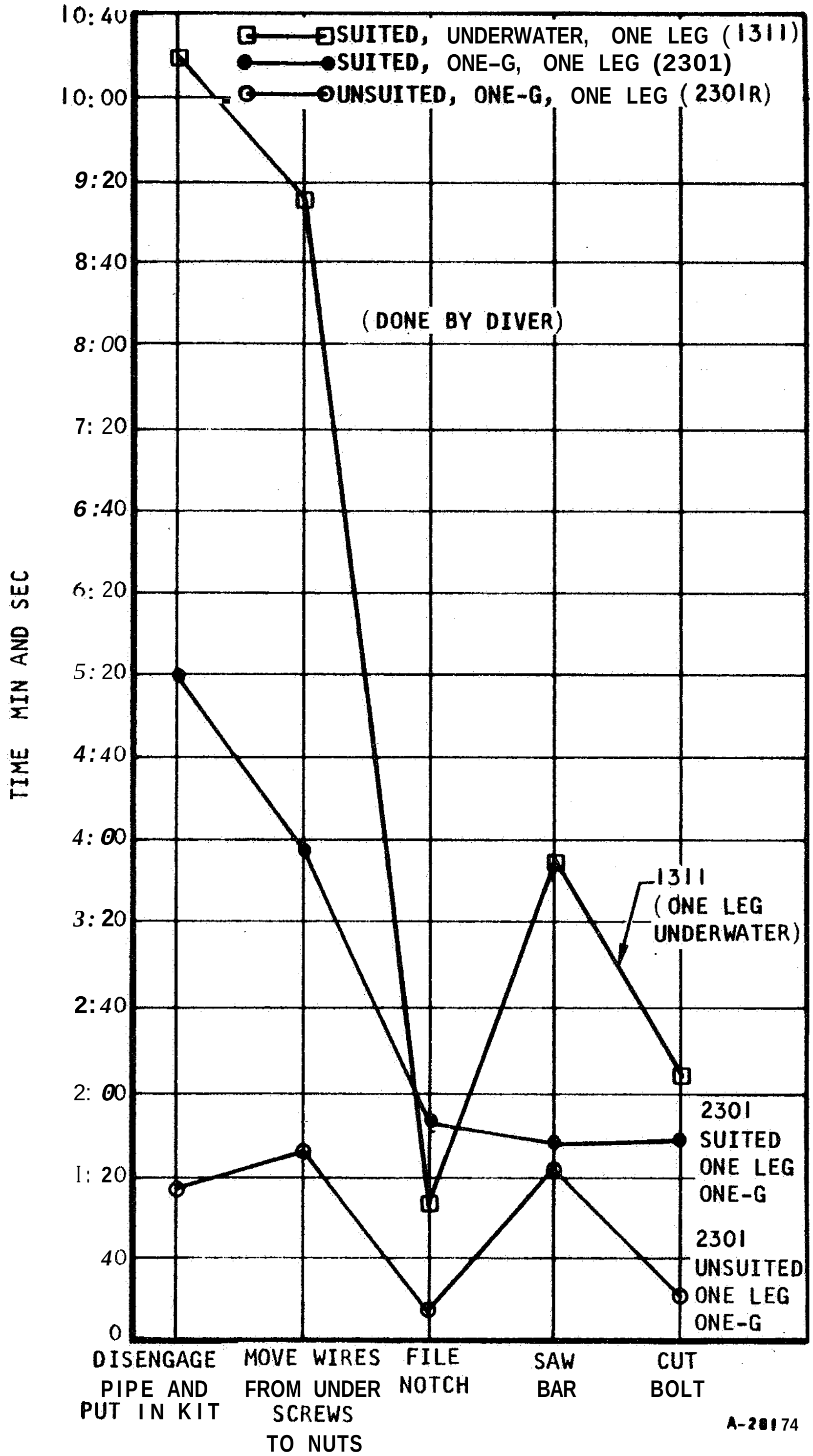


Figure 6-21. Comparative Task Times for Work During Unsuited One-G, Suited One-G, and Underwater Zero-G Simulation Modes

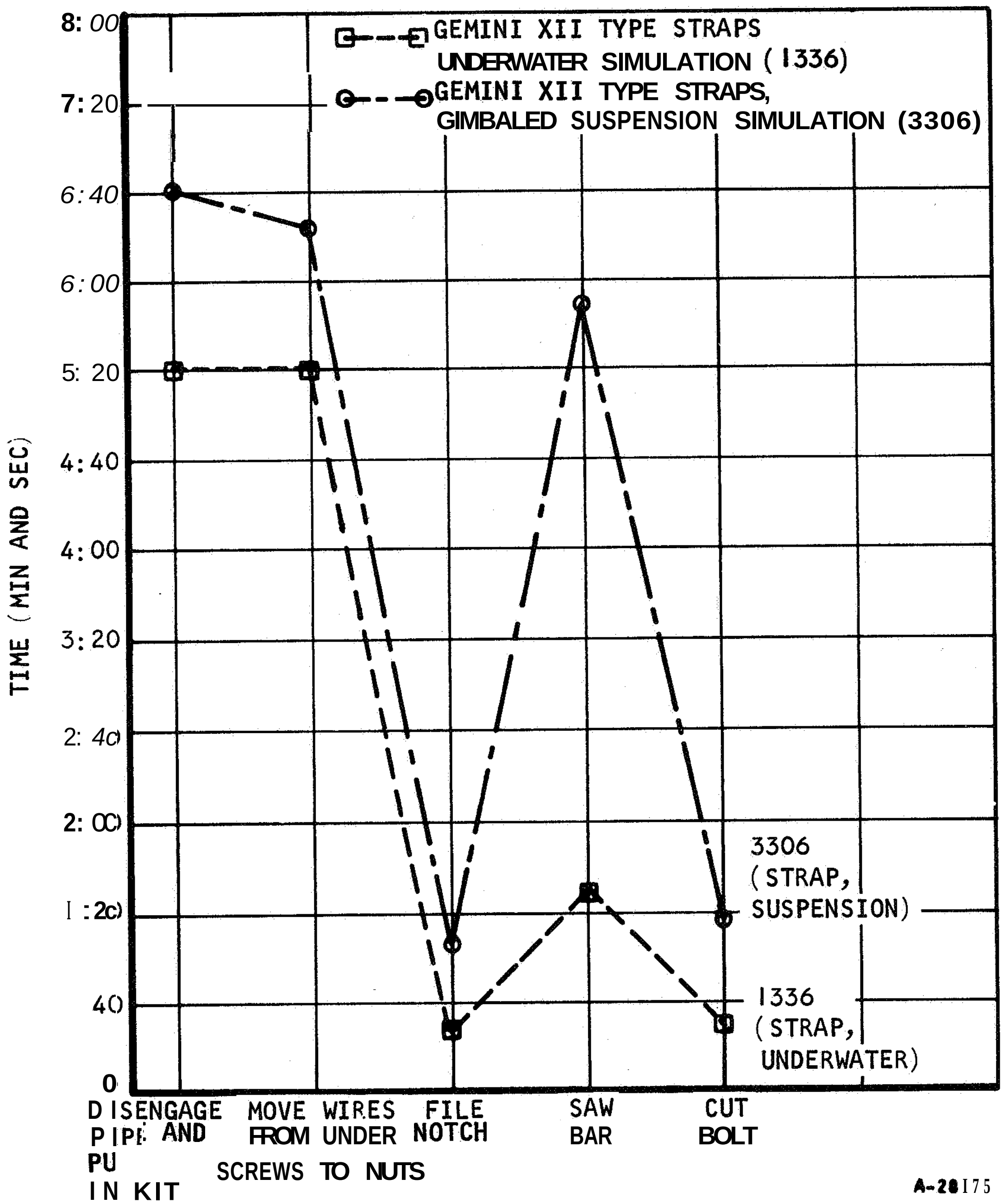


Figure 6-22. Comparative Task Times for Work using the Zero-G Suspension and Underwater Simulation Techniques

NUMERICAL RESULTS, SUMMARY, HYPOTHESES, AND CONCLUSIONS:

One of the deliberate choices made in planning this study was to permit contamination of the data and general sparcity of the data to facilitate breadth of coverage. The benefits of such a strategy are seen in the first part of the results section, which gives a great deal of detailed information on weightless work. This type of information becomes the basis for an engineering "feel" for the problem of weightless work. The alternative to broad coverage would have been deep coverage of some aspects of weightless work. Without an initial broad study it is almost a certaintly that such depth would have been misplaced. For example, a detailed, controlled study for restraints would not have uncovered the problems involved with fasteners and clamps.

The price paid for the "feel" for the problem was numerical data of limited usefulness. This is a low price when one considers that in most new technology development, numerical data are used relatively late. This section on numerical data has shown how such data can be used. It has also shown how such data can be interpreted in the light of a task taxonomy. A final, general trend in the discussion of thenumerical data is the dependence of number interpretation on the work positions, tools, hand grasps and the other items that consitute a human engineering "feel" for the problem. The discussion of the numerical data in this section leads to the following hypotheses and conclusions

a. <u>Hypotheses</u>

1. Task success data are a valid indicator of the value of work aids and the difficulty of tasks.

2. Time data can be organized so as to indicate the value of work aids and the difficulty of tasks.

3. A task taxonomy can be formulated such that work aids rank order consistently within classes.

4. The Gemini XII type of strap restraint is best for tasks requiring force opposing the tension of the straps.

5. The birdcage restraint system is best for tasks requiring mobility while restrained.

6. The foot-strap restraint is best for (a) tasks requiring prolonged dexterous work in place and (b) tasks requiring force not opposing the position tension.

7. Time data can be used as a trade-off guide in (a) the choide of work aids and (b) the planning of development programs.

b. Conclosions:

1. Numerical data must be interpreted in conjunction with the mechanisms of task performance noted by a competent human engineering observer.

2. In experiments where the analytic results are important, depth must take precedence over breadth. This has three principal corollaries:

   (a) The effects of time variables such as learning, fatigue, and warm-up must be controlled.

   (b) Enough subjects must be used to provide statistically dependable comparisons.

   (c) Experimental conditions must be planned so that comparisons are uncontaminated by irrelevant differences between data points.

SECTION 7

PHYSIOLOGICAL RESULTS

GENERAL

Although the major emphasis in this effort was to assess the human engineering and human factors durinq simulated EVA task performance using the neutral buoyancy technique, physiological data were obtained to monitor the well being of the subjects and to measure the physiological costs of performing EVA tasks in real time. All testing was exploratory in nature, and the physiological data obtained represents the changes which occurred and cannot be compared with data derived under laboratory conditions, The exploratory tasks presented questions such as, "Can a man perform this particular job and how long does it take?" The subjects were allowed to set their own work pace and to modify tasks just to get them done. Thus, the physiological data can be compared between types of simulation only in terms of values at rest, peak values, and in correlation to human factors observations.

Metabolic rates, heart rates, and respiratory rates were measured during the performance of the various tasks described previously in each of the one-g, zero-g six degrees-of-freedom simulation, and neutral buoyancy conditions. The acquisition of these data were secondary objectives of the tests, and tests were not delayed or aborted if the physiological sensor systems did not function.

METHODS

The techniques utilized to obtain the physiological data were modifications of standard methods. Two subjects were studied. Their physical characteristics are presented in Table 7-I.

TABLE 7-I

ANTHROPOMORPHIC

Subject	Age yr	Weight kgm	Height cm	Body Surface Area m^2
M. G.	23	70	178.5	1.81
G. R.	43	78	165.5	1.89

METABOLIC RATES

The basic system configuration was presented in the section on apparatus. The subject's oxygen consumption was calculated from raw data obtained on the gas flow through the pressure suit and the change in oxygen concentration between the inlet and outlet fittings of the suit. Gas flow was controlled and measured using either a Texas Instrument mass flowmeter or a calibrated orifice flow section. The appropriate pressure and temperature measurements were made to allow corrections to standard pressure, temperature, and dry conditions. Suit inlet and outlet oxygen concentrations were measured using a CEC cycloidal type of mass spectrometer. A major assumption in the use of this technique is that there was complete mixing of the respired gases with the suit flow gas. Sampling was performed at the instruction of the test coordinator and data points were chosen to coincide with the subject's activities. Metabolic rates were calculated by the equations presented later in this section.

ELECTROCARDIOGRAPH

Continuous electrocardiograms were recorded using a three-electrode system consisting of a bipolar modified Y-4 lead and a ground. Recording and monitoring was done on a two-channel recorder. All tracings were made at a paper speed of 5 mm per sec.

RESPIRATORY RATE

Respiratory rate was monitored by a short-time constant thermistor attached to the boom microphone of the pressure suit helmet. The output of this instrument was recorded on the Beckman two-channel recorder at a paper speed of 5 mm per sec. Respiratory rate was obtained as the excursions of the thermistor signal corresponding to the temperature fluctuations of the inspired and expired respiratory gas.

In order to plot a time profile of ECG and respiratory rate changes with activity, a more comprehensive approach on data collection was made in the later tests. This was done in an attempt to note the effect on the subject of the various steps during subject preparation. Data points were taken for the following intervals.

a. Subject in position on the platform with cables attached, visor open, no weights attached

b. Visor open, weights attached

c. Visor closed

d. Pressurized prior to descent

e. Descent to bottom

f. On bottom

g. Work session, intervals at direction of test conductor

h. End of work

i. After ascent visor closed

j. Depressurized, visor open

RESULTS

The physiological data obtained during one-g are shown in Figures 7-1 through 7-6, during neutral buoyancy in Figures 7-7 through 7-17, and during zero-g simulation in a six-degrees-of-freedom gimbal simulator in Figures 7-18 and 7-19.

In comparing these data, several differences are noted. These differences are shown in Table 7-2. The rest values for metabolic rates are averages for at least six determinations and the maximum measured values are single observations.

TABLE 7-2

COMPARISON OF METABOLIC RATES
Btu/hr

Simulation	Rest	Maximum Measured
One-g	697	3243
Neutral buoyancy	1035	2170
Zero-g six-degree-of-freedom	478	3489

It is evident that there is a simulation effect on the data obtained. For example, the resting rate in zero-g is less than one-g, which is less than the neutral buoyancy values. The lower zero-g values are the effect of a man being completely supported so that the metabolic cost of maintaining balance and posture were not factors in determining the total metabolic rate. The additional metabolic cost in the one-g simulation represents the additional cost of the use of postural muscles and a greater heat load. The twofold increase noted with neutral buoyancy results from the subjects' having to exert a reactive force to maintain balance and position during the simulation and the temporal error induced by the long sample lines used in the underwater simulation.

The high peak values of the zero-g simulation result from the high cost of providing the reactive force necessary to accomplish any task, Throughout these work sessions the subjects complained of not being able to achieve and maintain a desired position, and had to exert a tremendous effort to accomplish even a simple task. It is interesting to note that the highest metabolic rates were measured during the maintenance tasks and particularly with the removal of the maintenance box, This resulted from problems in positioning to reach the retaining bolts, Filing, drilling, and sawing were also major problems in the zero-g configuration.

The lower peak values seen with the underwater studies are complicated by several factors, It is probable that the thermal loss of the subject is increased and results in lower metabolic rates, There also exists the effect of the drag introduced by the water medium, and also the relative ease with which the subject could bend the suit in the water medium as compared to an air environment. The role of thermal exchange and bending forces in the suit are areas which require clarification in future studies. It should be noted that the greatest portion of the decrease in metabolic rates is probably due to the subjects' being able to take better advantage of their restraint systems during underwater simulations.

In general, metabolic rates remained below 2000 Btu/hr regardless of simulation techniques, Heart rates were never greater than 140 beats per min during underwater tests, and thus compare with those seen on Gemini XII. The highest heart rates were noted during zero-g simulation where they reached 155 beats per min during a drilling exercise.

Sweating was a major problem with all modes of simulation and work tasks. Start of sweating could not be correlated with metabolic rates, This points to the need for body core temperature measurements and even thermal exchange with the atmosphere to evaluate sweating, metabolic rates, and work,

In attempting to evaluate the stepwise procedures in subject preparation for the effects of visor closure, pressurization, descent to the bottom and ascent from the bottom, it is obvious that the activities performed by the subject and his handlers completely masked any effect which might have been present. From these data one can say there was no emotional stress in anticipating the tasks. Heart rates showed no peaks which would indicate emotional stress. In fact, this was true throughout all tests, indicating the emotional stability of the subjects and their acceptance of the various environments.

Figure 7-20 presents the correlation between metabolic rate and heart rate replotted from Figures 7-13 through 7-15. As expected, heart rate increased with metabolic rate, but only in the test with construction of the large rigid module does there appear the linear relationship noted with calibrated subjects performing controlled exercise in a constant environment. Plots of all tests were made, and the rigid test was the only one yielding the relationship. Most plots resulted in scatter grams as seen with the folding panel application in

Figure 7-20. Therefore, within the constraints on the data imposed by exploratory testing, it would be impossible to derive metabolic rates from heart rates even for calibrated subjects. The discrepancy between heart rate and metabolic rate probably lies in differences and/or lack of thermal balance during testing. Brouha (ref. 22) has reported the effect of heat on this discrepancy. He further indicated that if work is performed at high temperatures, full physiological recovery lags far behind that of the oxygen consumption. A thermal evaluation for this type of testing is therefore essential to completely understand the heart rate-metabolic rate relationship.

An analysis of respiratory rate data shows little or no correlation to the subjects' activity or work performance. Since respiratory rate is greatly influenced by psychic control, it seldom correlates with work patterns. Respiratory rate is a useful physiological monitoring measure source, hyperventilation can be easily identified.

The metabolic rate data obtained within these studies had several sources of error other than those imposed by the analytical instruments themselves. It is important to understand these sources of error and the limitations they impose upon the data. The sources of measurement error included:

a. Analytical instrument error.

b. Outboard leak from the suit which would result in gas concentration changes.

c. Measurement of oxygen fraction is influenced by the mixing of various volumes of respired gas with suit flow gas at different work rates. For example: at rest 6 to 10 liters of respired gas (16 to 17 percent oxygen) is diluted in the same flow.

d. Gas sampling 100 ft displaced from the subject. The transient times for gases tends to average data over time and decreased the correlation between measured metabolic rates and the actual work being performed. The time lag minimizes the usefulness of the data as real-time data.

e. Gas mixing in helmet resulting in a decreased inspired oxygen concentration from that measured at the suit inlet. This results in by far the largest effect on metabolic rate calculations.

Although not a measurement error, the suit environment and ambient environment both affect the thermal balance of the subject which has a direct effect on the metabolic rates.

In order to evaluate the order of magnitude of the errors involved in these measurements, an error analysis for the worst possible case was performed. This worst case results when only a systematic error is involved for all the various sources of error and all errors are additive. For these tests the error in determining oxygen consumption is calculated by:

$$\dot{V}_{O_{2STP}} = (I \left(F_{IO_2} - F_{EO_2}\right) \frac{P_A + P_F}{P_A} \times \frac{TR}{T_R + T_F} \qquad (7\text{-}1)$$

where $\dot{V}_{O_2}$ = O_2 consumption (L/min STP)

$F_{I_{O_2}}$ = fraction O_2 inspired

$F_{E_{O_2}}$ = fraction O_2 expired

= absolute pressure

= gauge pressure of flow transducer

P_F

T_R = absolute temperature

= temperature at flow section

T_F

$$\text{Metabolic rate} = \dot{V}_{O_2} \times C \times K \times 60 \qquad (7\text{-}2)$$

where C = caloric equivalent per liter of O_2 at an assumed R. of **0.85 = 4.822 kcal/l.**

k = Btu equivalent per kcal = ***3.96***

if a = accuracy of V

b = accuracy of $F_{I_{O_2}}$

c = accuracy of $F_{E_{O_2}}$

d = accuracy of P_F

e = accuracy of T_F

assuming a no leak system and

a = flow section error of l percent = 0.01

b = mass specification error = l percent + reading error of **2** values of l percent full scale reaching = 0.01 + **0.002** + **0.002** = **0.014**

c = same as b above = 0.014

d = monometer reading of 1 percent = 0.01

e = thermocouple to recorder error of 10.8 percent = 0.008

Then, if all errors were systematic rather than random, the error would be calculated by

$$\text{Maximum error } V_{O_2} = a + b + c + d + e$$

$$= 0.01 + 0.014 + 0.014 + 0.01 + 0.008 \qquad (7\text{-}3)$$

Also

$$\text{Metabolic rate} = C \times k \times 60 \times V_{O_2}$$

Assume that an error in C is 2 percent = 1.5 percent resulting from assuming an R of 0.15

Error in metabolic rate = 0.02 + 0.015 + 0.056 = 0.094

Maximum error in metabolic rate = 9.4 percent

For nominal inlet suit suit of 4.5 cfm = 127.4 liter/min.

If suit leakage were equal to 1 liter/min per design specifications, the error in V_{O_2} would be 1/127.4 = 0.0078 or 0.8 percent. Then maximum error in metabolic rate = 9.4 percent + 0.8 percent = 10.2 percent if all error decreased metabolic rate value.

Another source of error exists in the use of suit inlet oxygen for $F_{I_{02}}$. In the helmet there is an incomplete washout of CO_2 and there is a residuum of approximately 1 percent CO_2 on the helmet. This would decrease the approximately 21 percent of oxygen by 0.04 percent (rest of 1 percent effect on N_2) effective oxygen. Thus, by using the inlet F_{O_2} the error becomes in the following example:

$F_{I_{O_2}}$ = 21 percent and $F_{E_{O_2}}$ = 20.5 percent

ΔF_{O_2} = 21 percent - 20.5 percent = 0.5 percent or 0.005

Actually ΔF_{O_2} = 21 percent - 0.04 percent - 0.46 percent or 0.0046

$$\text{The percent error} = \frac{0.005 - 0.0046}{0.005} = \frac{0.0004}{0.005} = 0.08 \text{ or } 8 \text{ percent}$$

Thus, this effect could be an overestimate of metabolic rate of 8 percent.

Assuming complete mixing of gases in the suit, the worst-case estimate of error would yield an overestimate:

$$\text{Maximum error} = F_{I_{O_2}} \text{ error from mixing} - \text{error from leak}$$
$$+ \text{ error from no leak analysis}$$
$$= 8 \text{ percent} - 8.8 \text{ percent} + 9.4 \text{ percent} = 16.6 \text{ percent}$$

This analysis is based on systematic error only. A mean sum of square analysis for random errors would reduce this value greatly.

There are several factors which do not lend themselves to error analysis and tend to yield an underestimate of metabolic rates. These include the mixing of the respired gases with suit flow which buffers the excursions of the metabolic rates and tends to provide a mean rate over time. This factor is further complicated by the approximately 100 ft of hose, which provides a time delay in measurement and acts as a further volume buffer. These factors override the error analysis presented above in trying to determine the correlation between actual work and metabolic rate. The technique for measuring metabolic rates as used in these tests is adequate for steady-state work modes—e.g., treadmill walking--but inadequate for short-duration work tasks.

CONCLUSIONS

a. There is a simulation effect on metabolic rates during rest and for peak rates. This effect is a result of differences in the requirement for the application of reactive forces between simulations and possible effect of thermal differences.

b. Metabolic rates are increased when a reactive force is applied in reduced gravitational fields.

c. Metabolic rates during underwater simulations normally ranged from 1500 to 1800 Btu/hr.

d. Heart rates never exceeded 140 beats per min with underwater studies. These rates compare favorably with those found on Gemini XII.

e. Respiratory rates showed no correlation with activity.

f. Heart rates did not exhibit a linear correlation with metabolic rates in these tests. This indicates that metabolic rates cannot be derived from heart rate for this type of simulation.

g. There was no correlation between sweating and metabolic rates.

h. An evaluation of the subjects' thermal balance during testing is necessary to completely evaluate the metabolic costs of work. The potential of an increased thermal loss from the suit underwater may have resulted in low metabolic rates.

i. Tests with a system which isolates the respiratory gases from suit flow are necessary if real-time data are to be obtained which can be correlated to work modes.

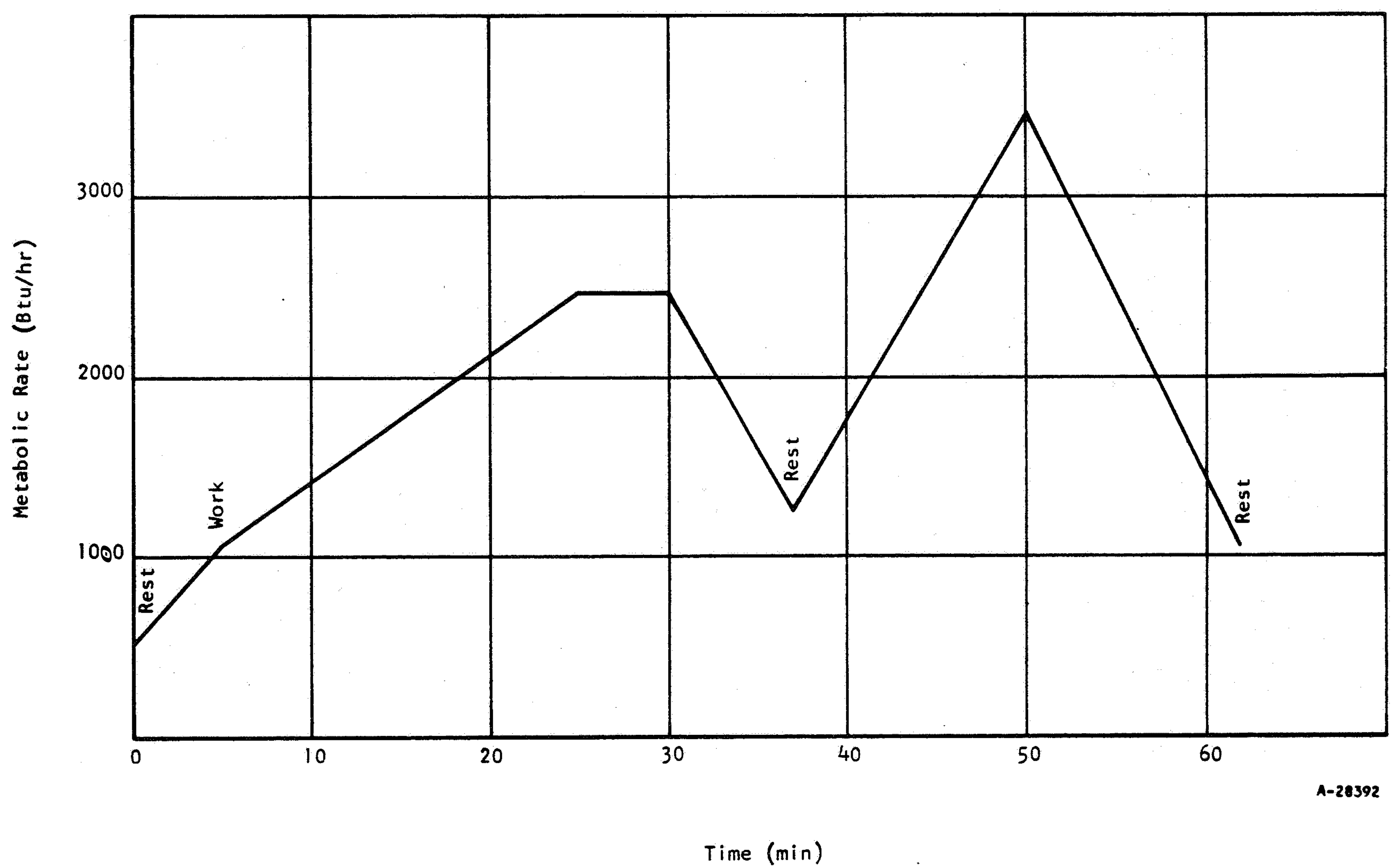


Figure 7-1. Maintenance Task at One-g, Test 2101

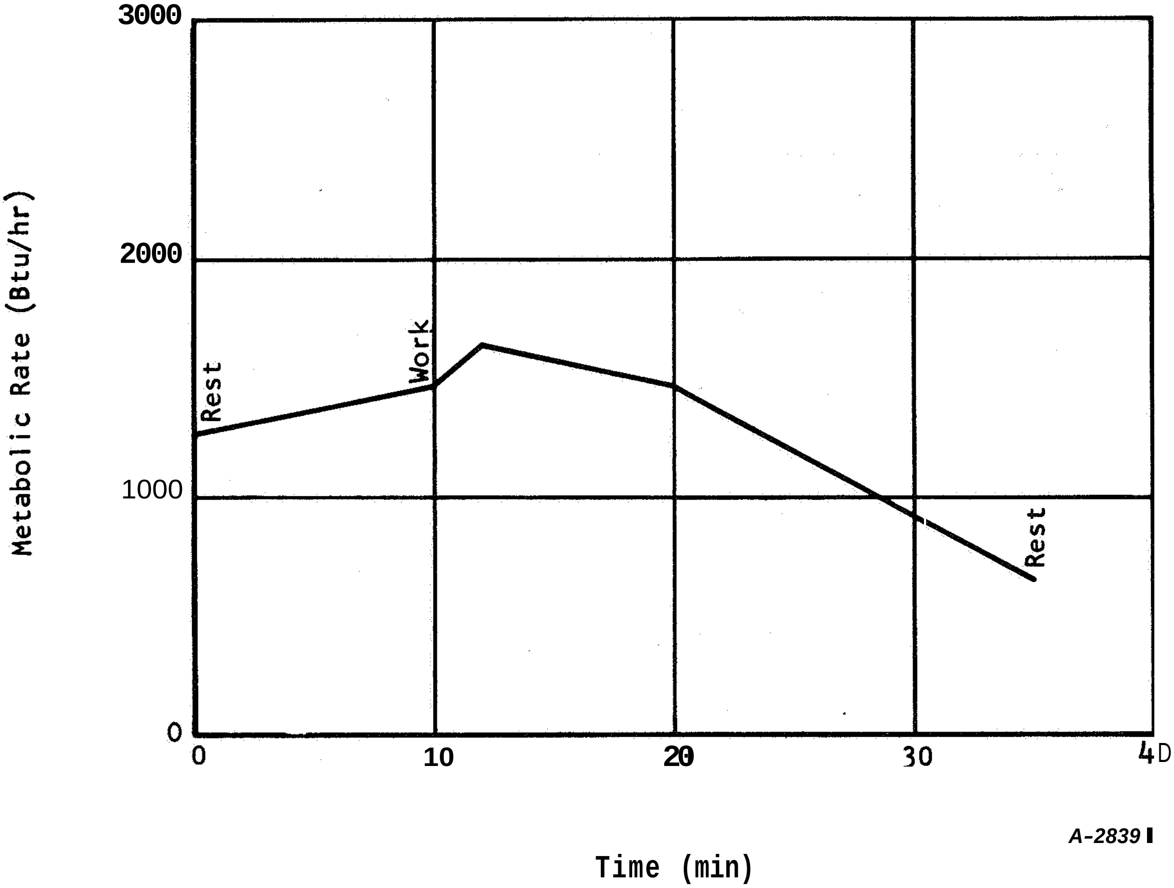


Figure 7-2. Maintenance Task at One-g, Test 2102

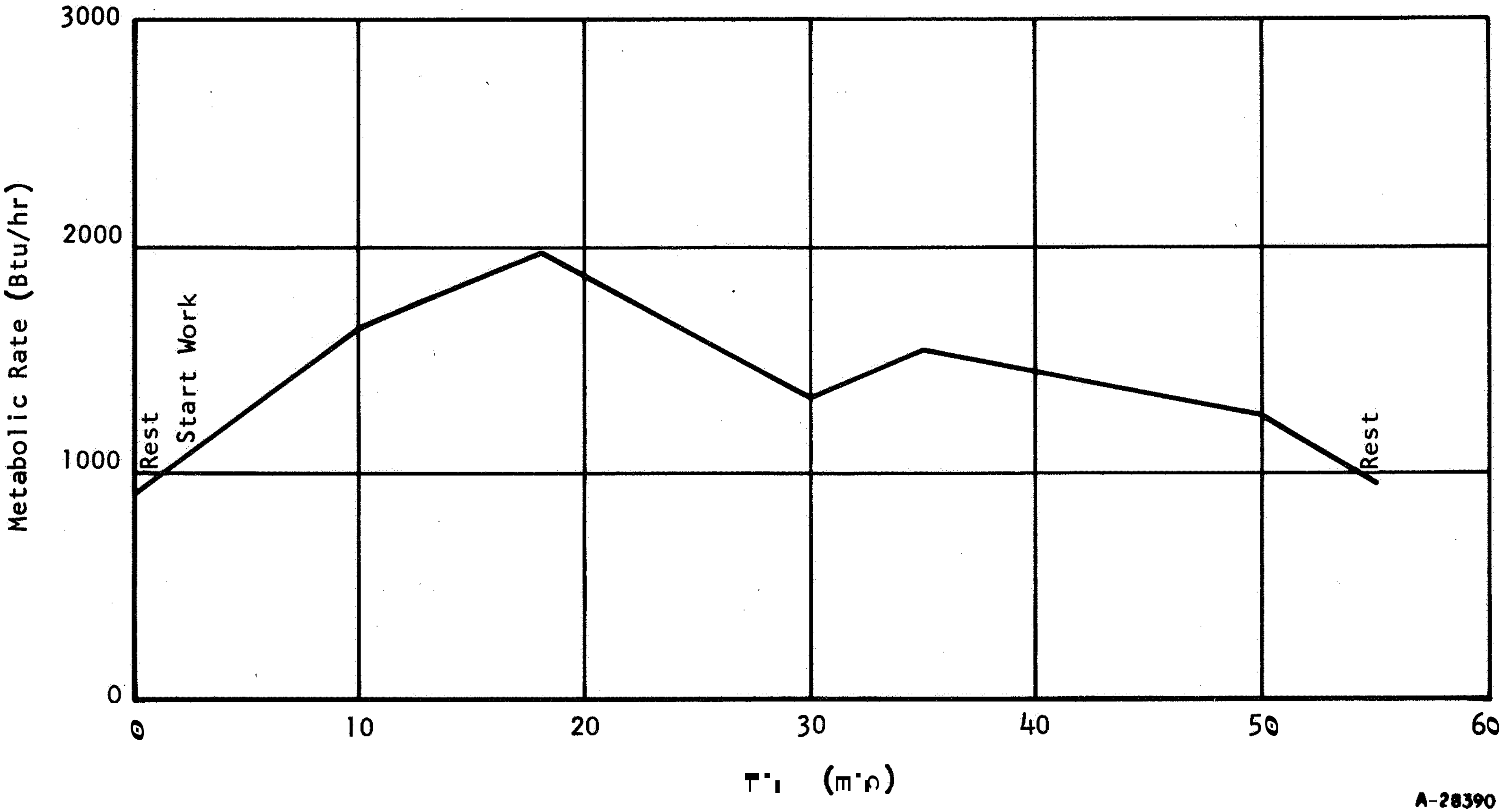


Figure 7-3 Maintenance Task at One-g, Test 2201

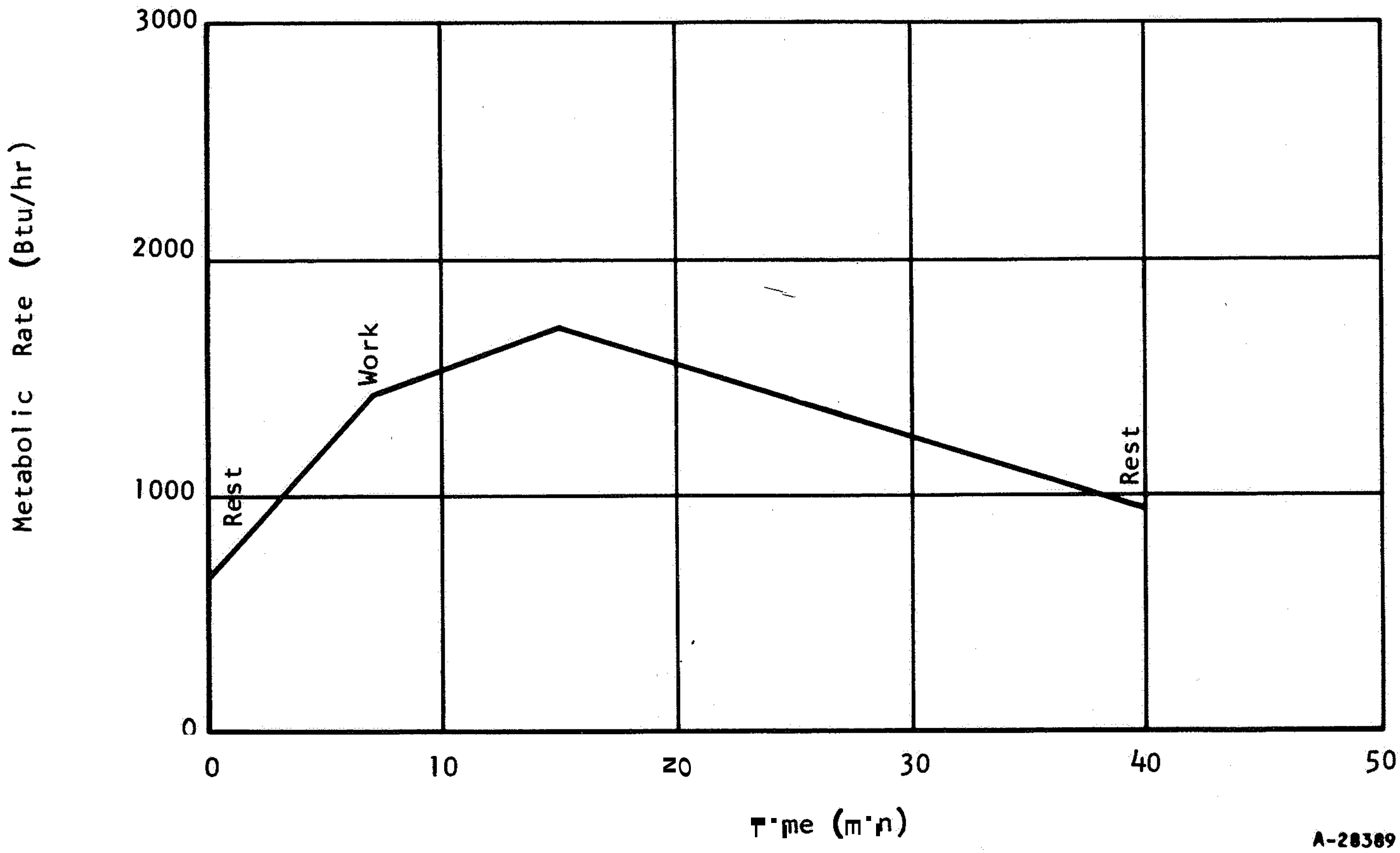


Figure 7-4. Maintenance Task at One-g, Test 2202

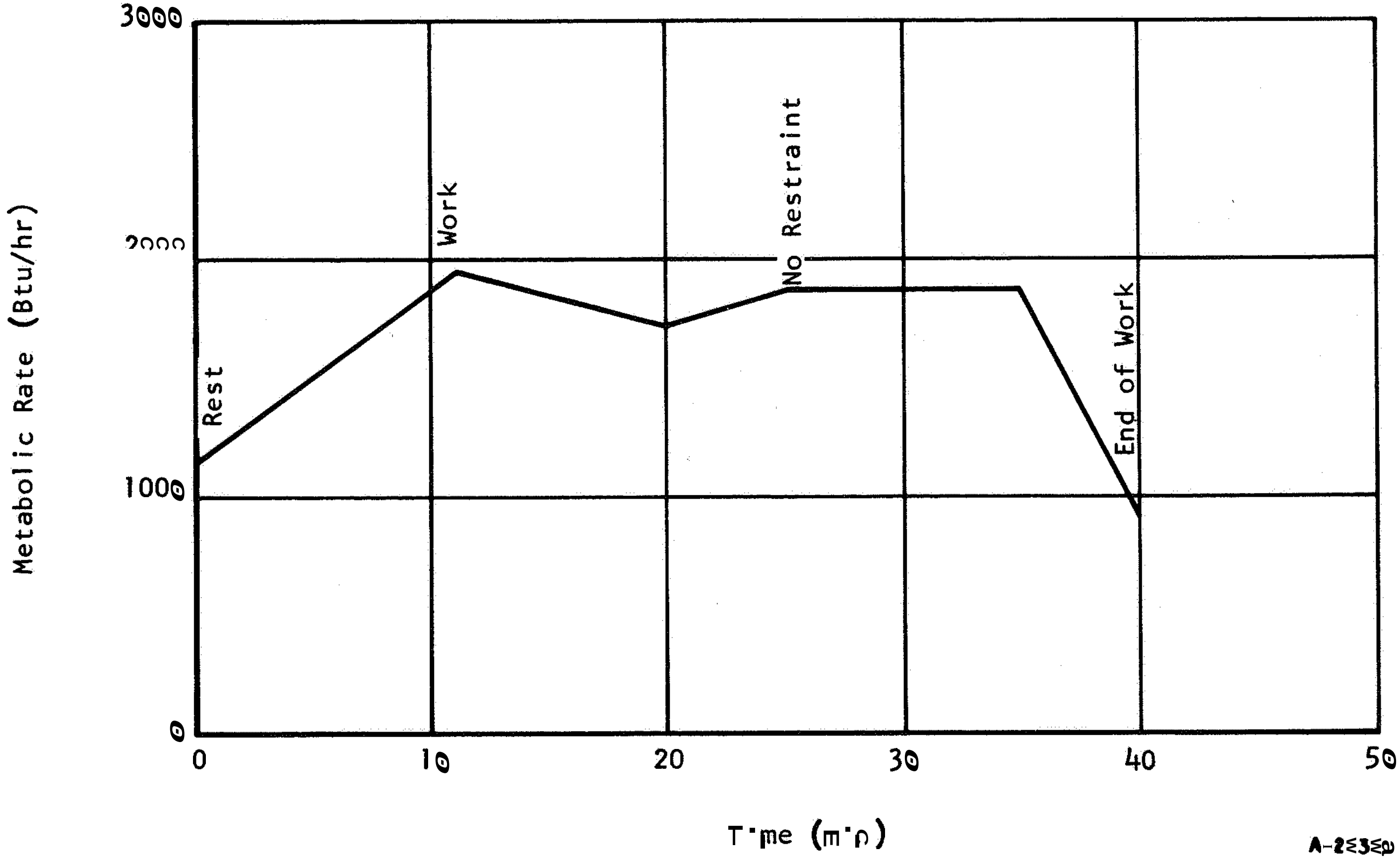


Figure 7-5. Maintenance Task at One-g, Test 2301

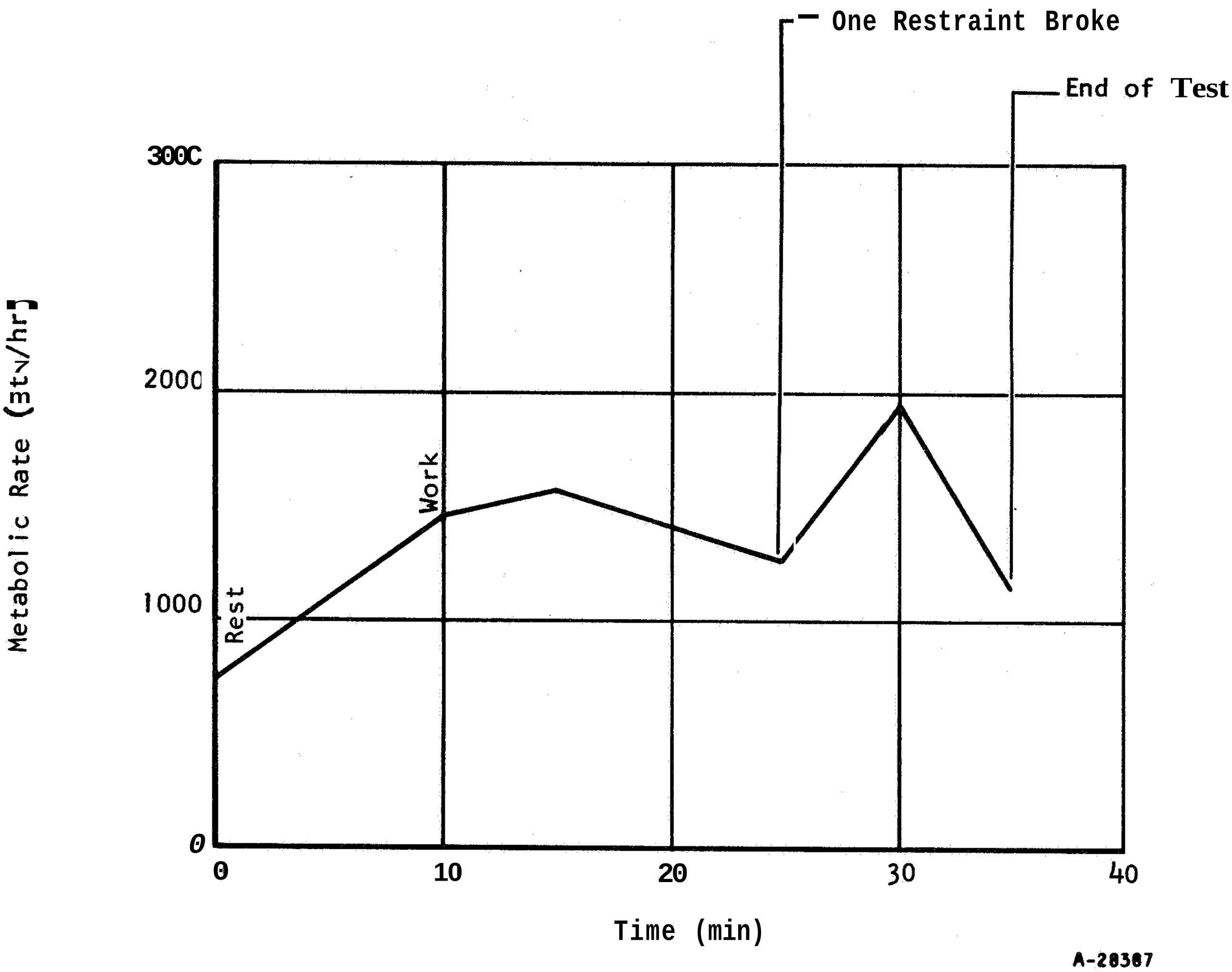


Figure 7-6. Maintenance Task at One-g, Test 2302

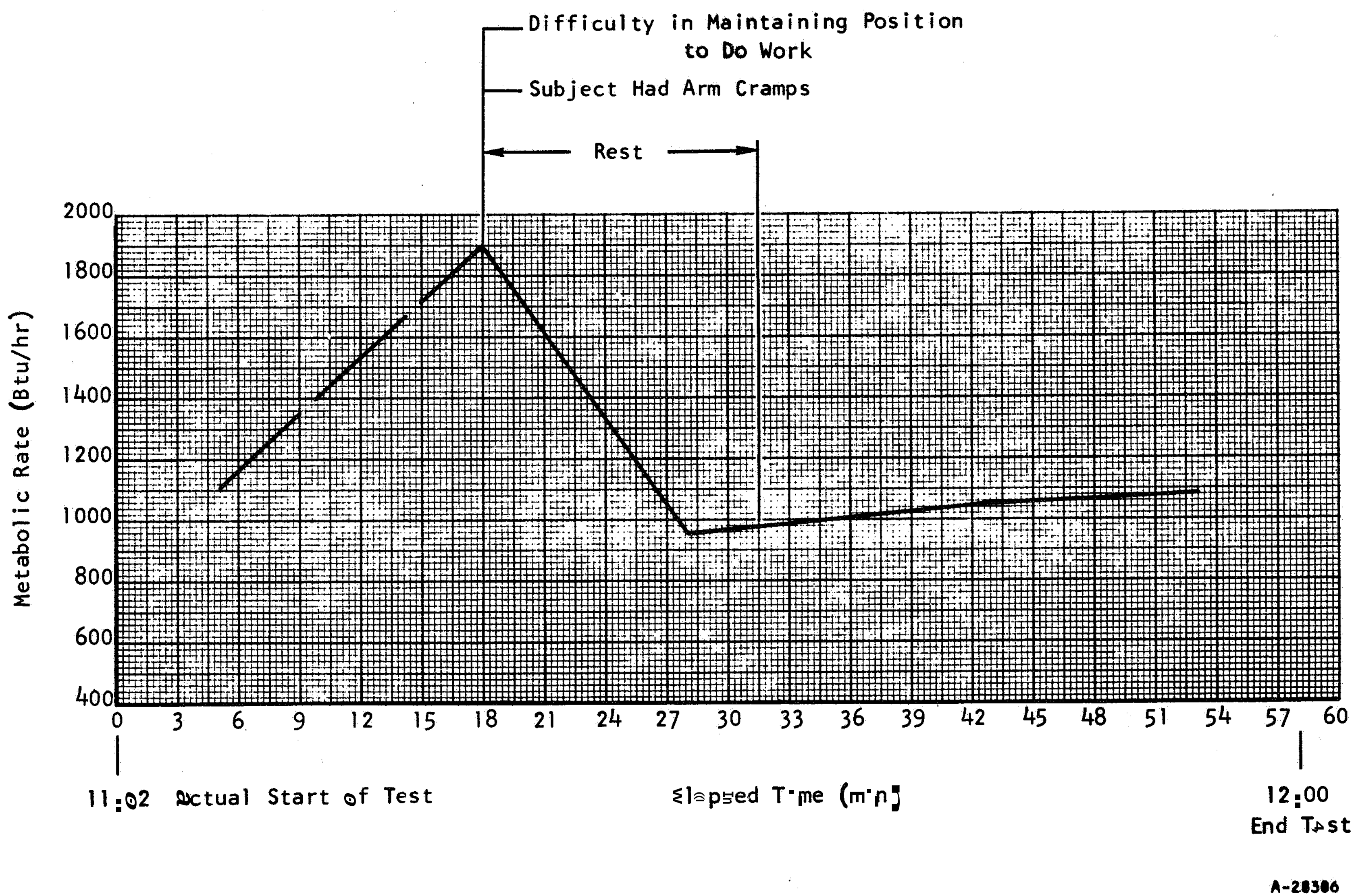


Figure 7-7. Maintenance Task During Neutral Buoyancy, Test I.I.I.I

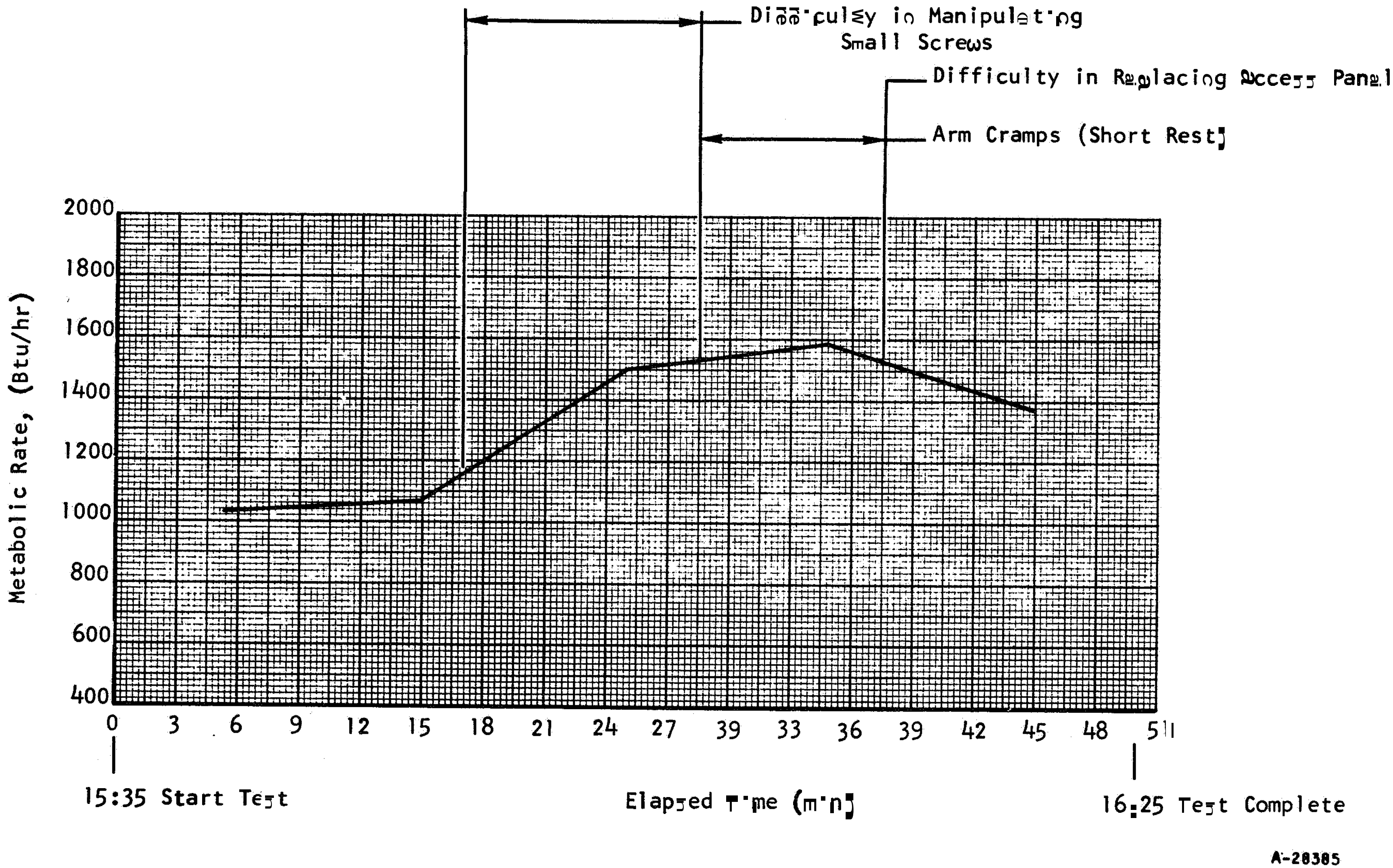


Figure 7-8. Maintenance Task During Neutral Buoyancy, Test I I C C

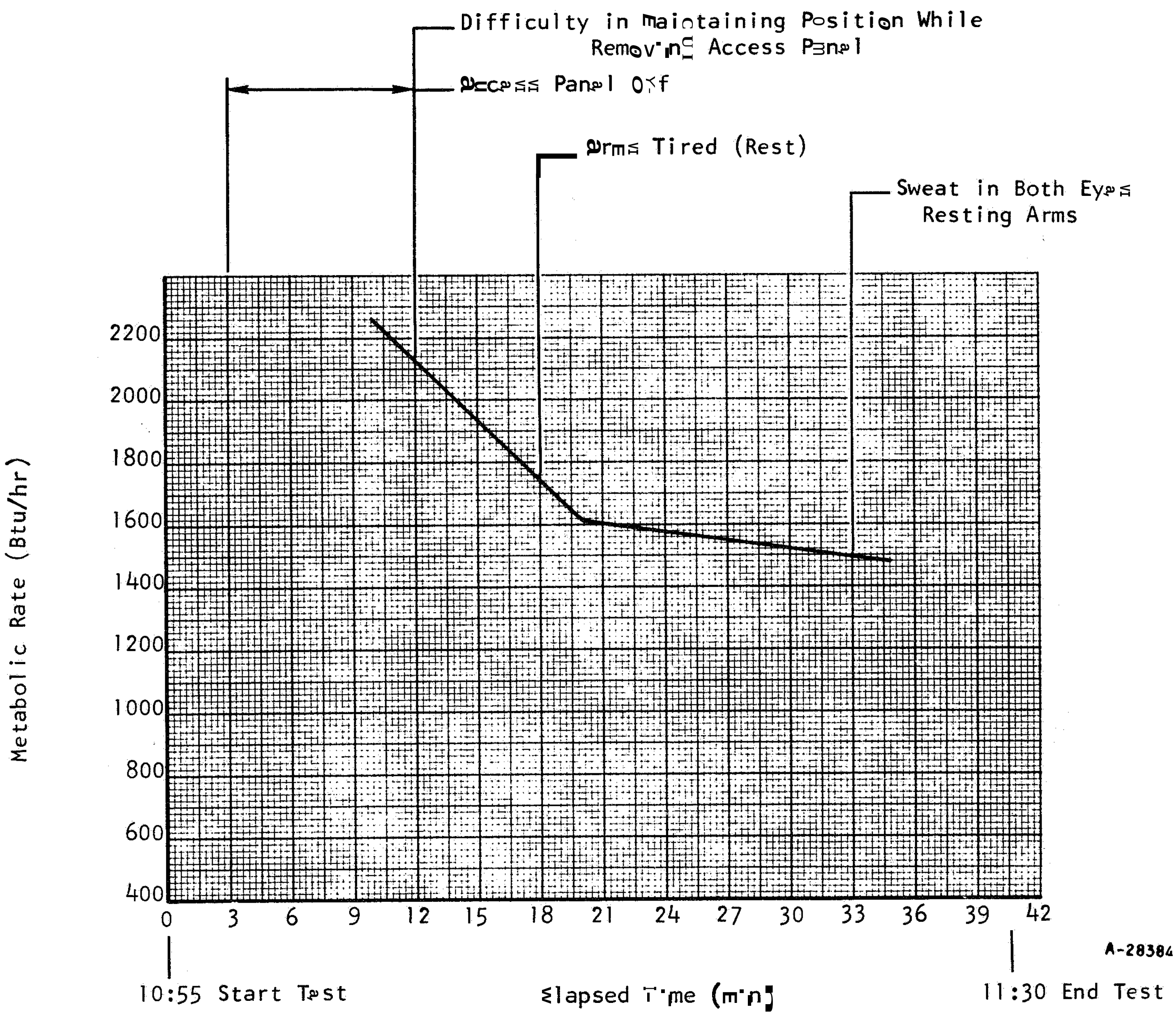


Figure 7-9. Maintenance Task During Neutral Buoyancy, Test 1.2.4.4

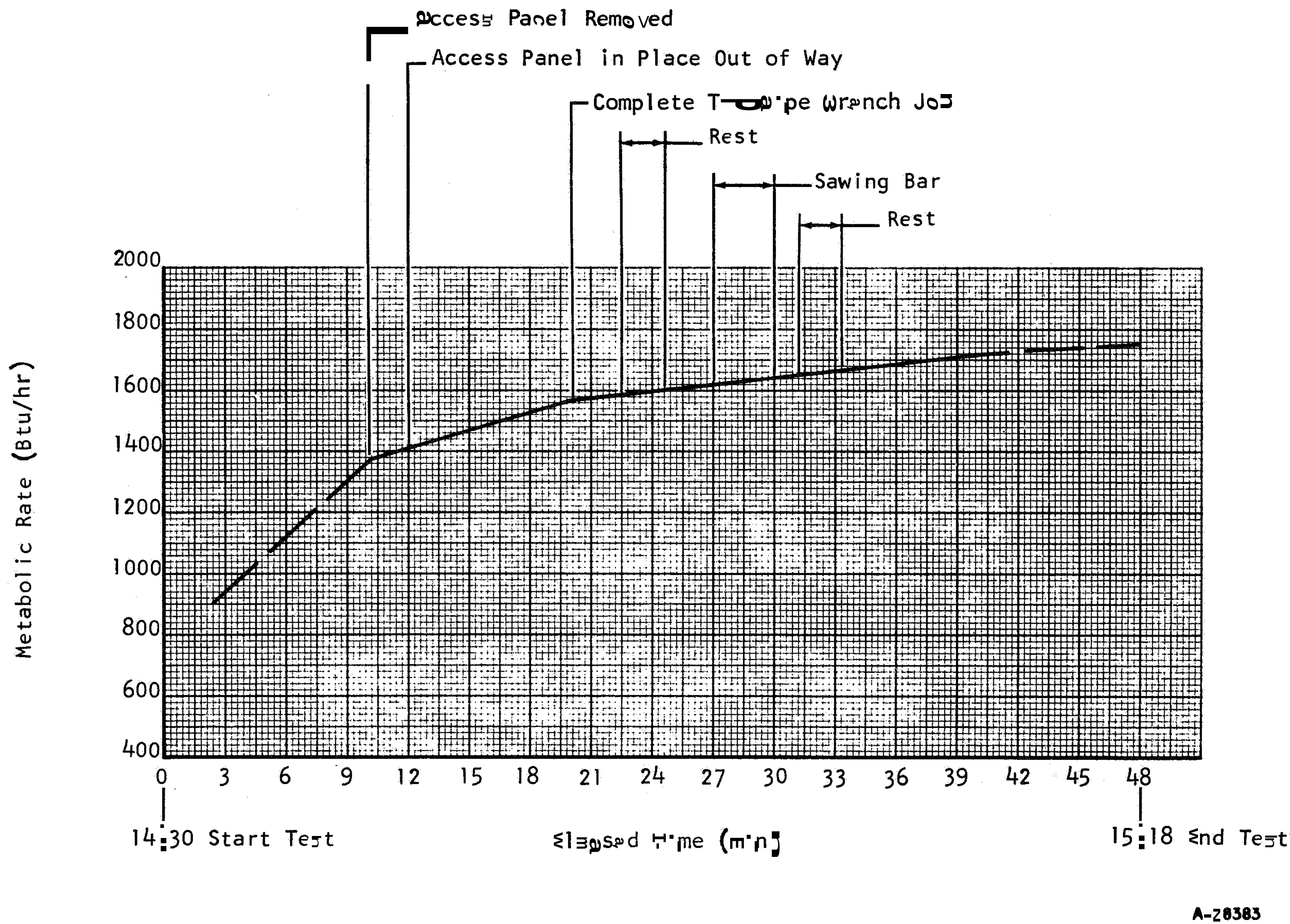


Figure 7-10. Maintenance Task During Neutral Buoyancy Test 1 3 0 0

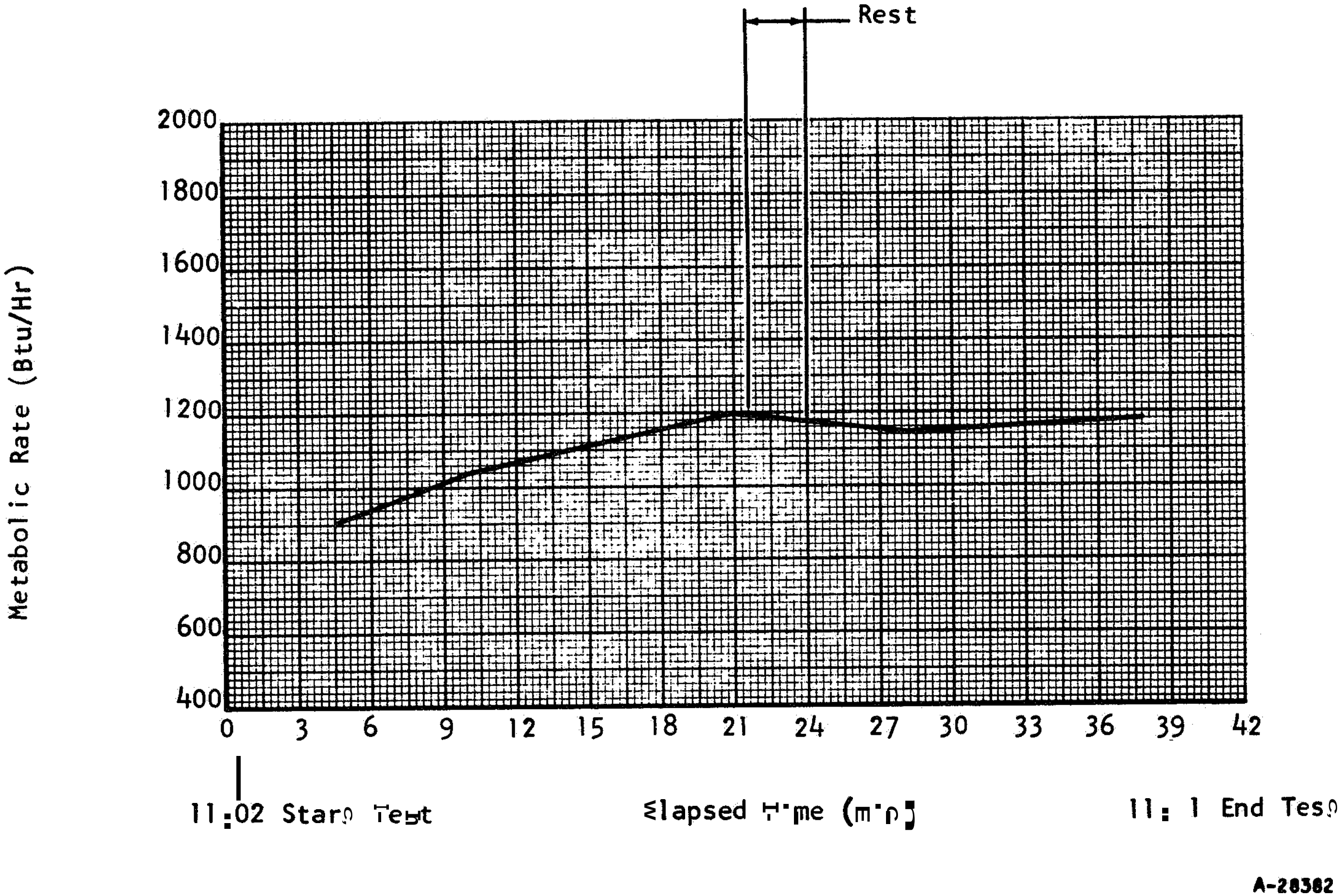


Figure 7-11. Maintenance Task During Neutral Buoyancy, Test 1.3.5.5

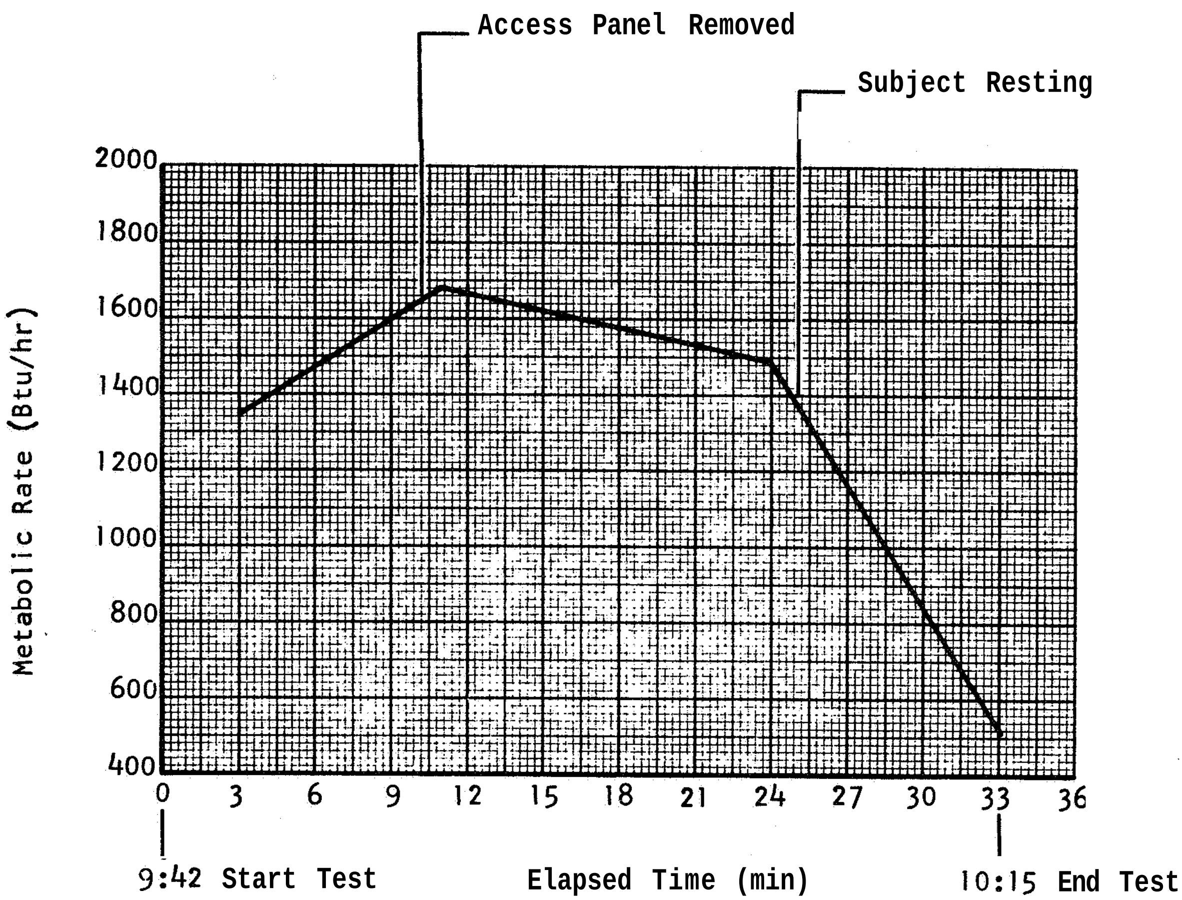


Figure 7C-12.

A-2038 I

Figure 7-12. Maintenance Task During Neutral Buoyancy, Test I. 1.5.5

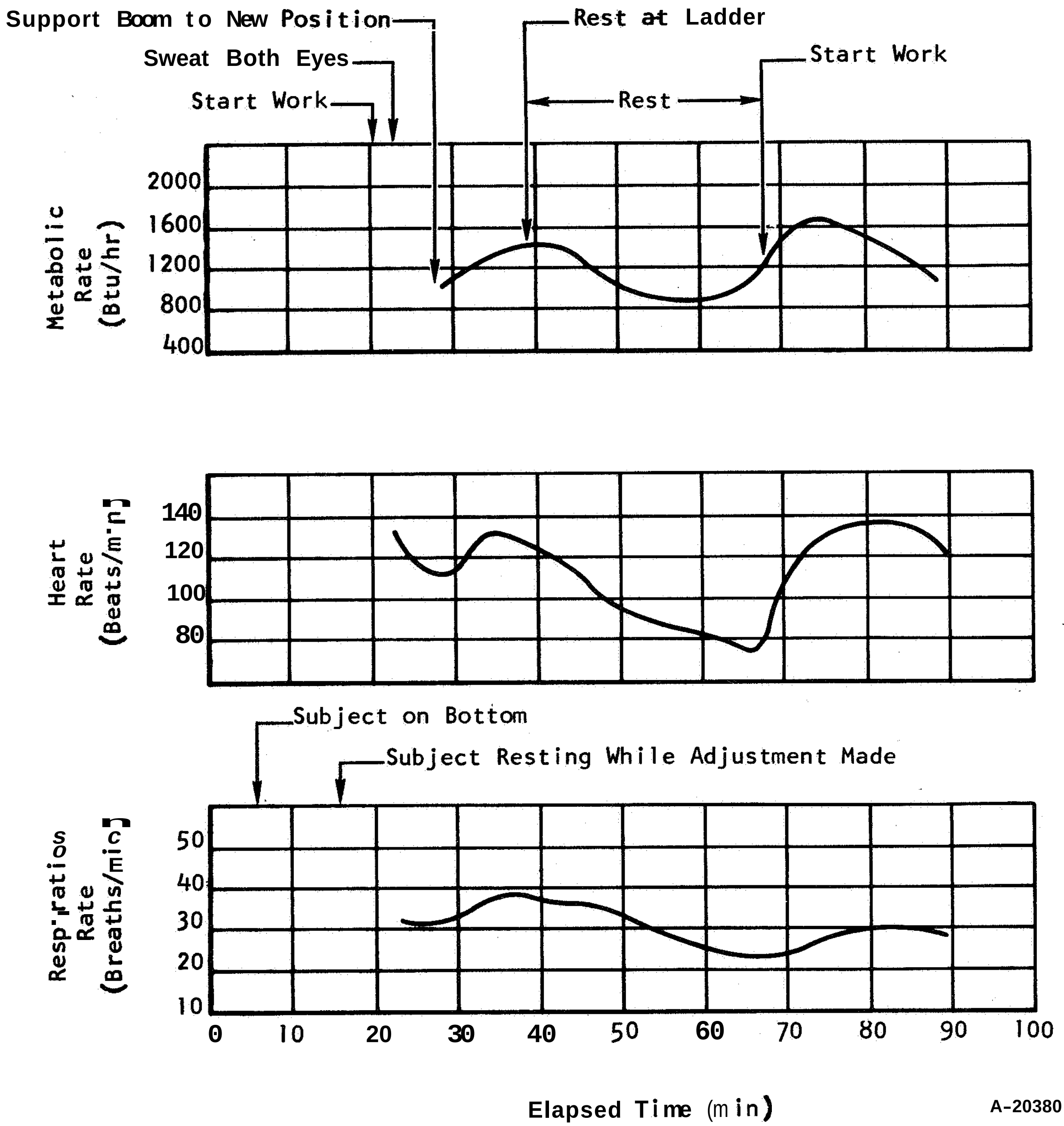


Figure 7-13. Physiological Data for Antenna Erection Tests

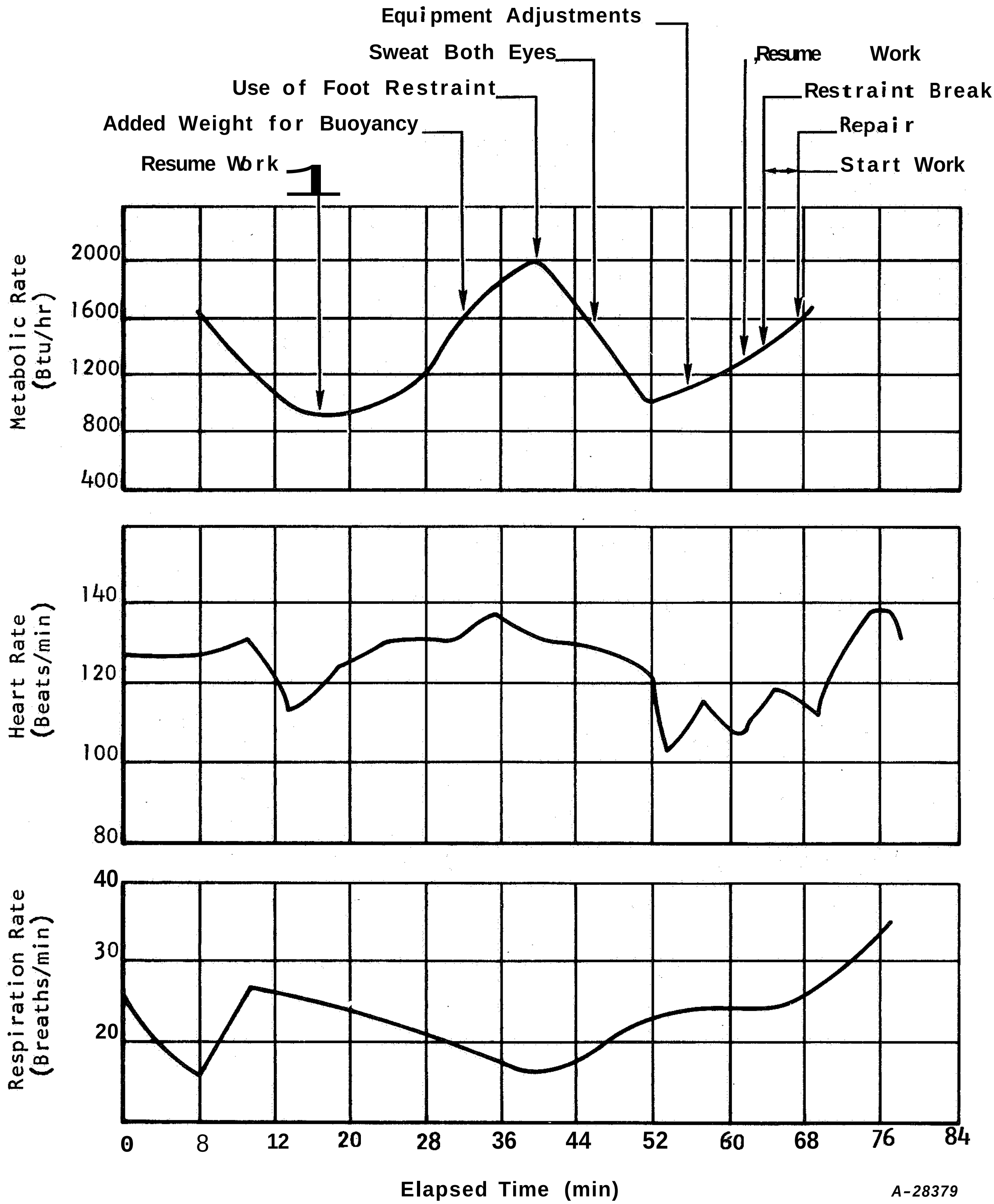


Figure 7-14. Physiological Data for Panel Placement on the Antenna

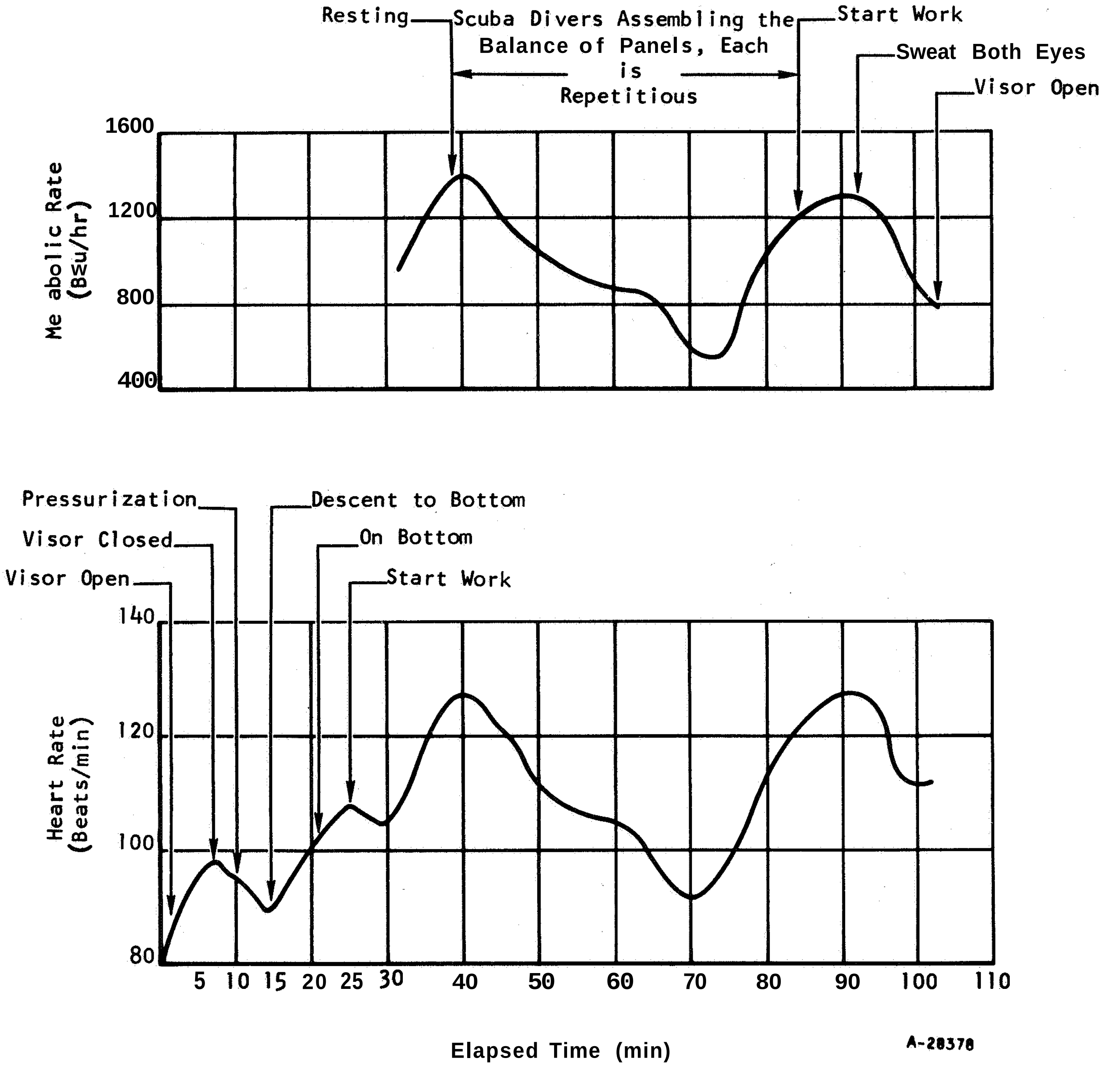


Figure 7-15. Physiological Data for Large, Rigid Module Tests

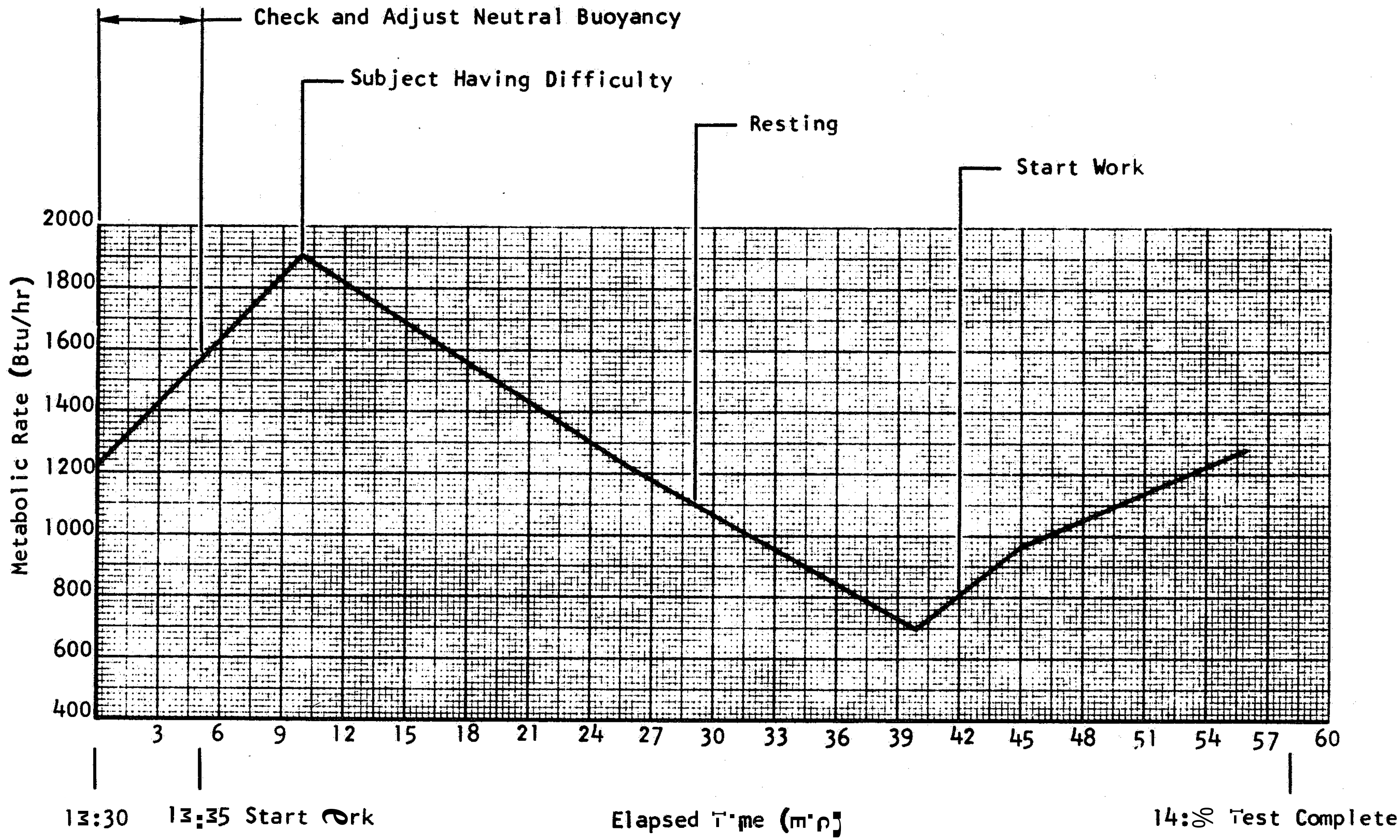


Figure 7-16. Assembly of Large, Rigid Modules, Neutral Buoyancy (Part 3 of 3)

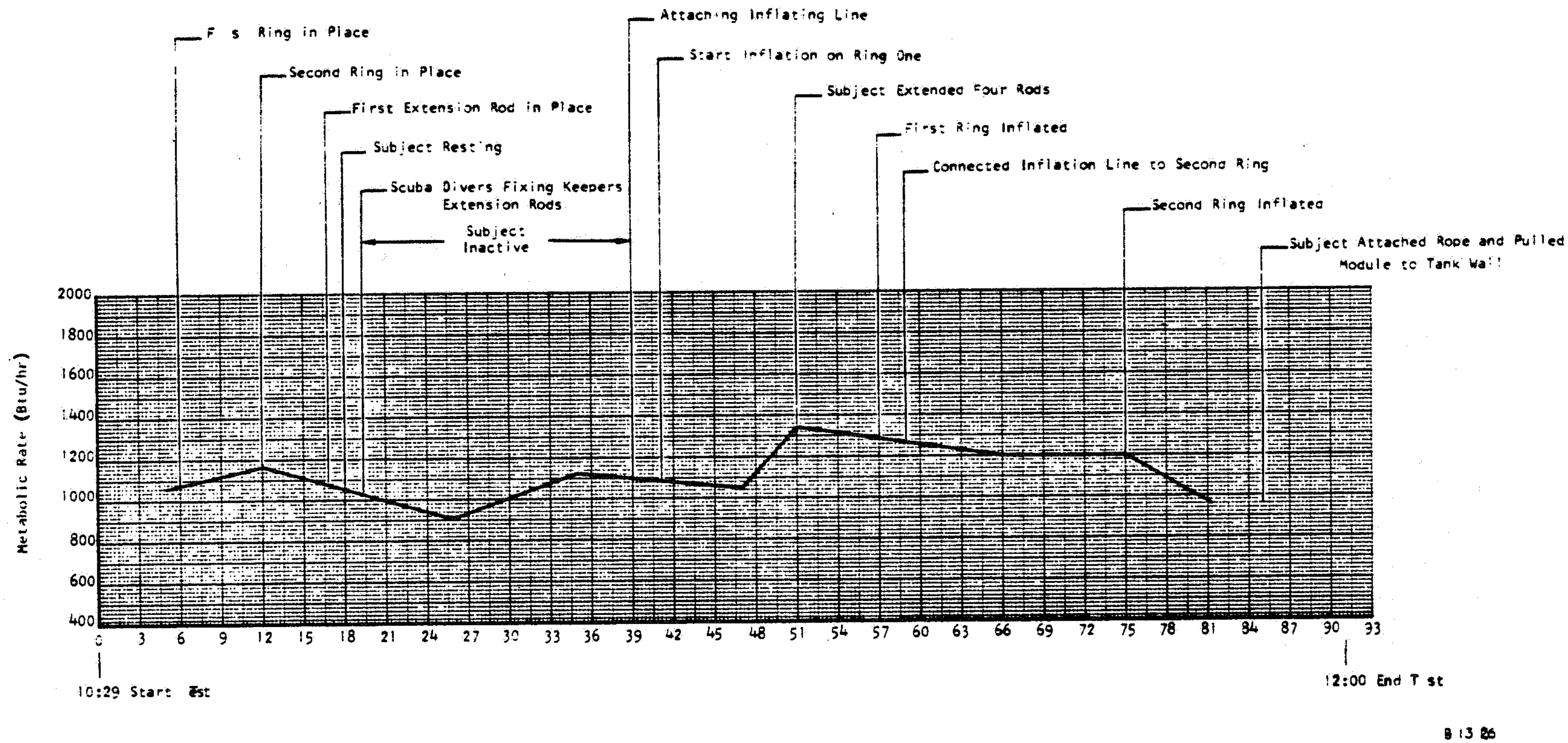
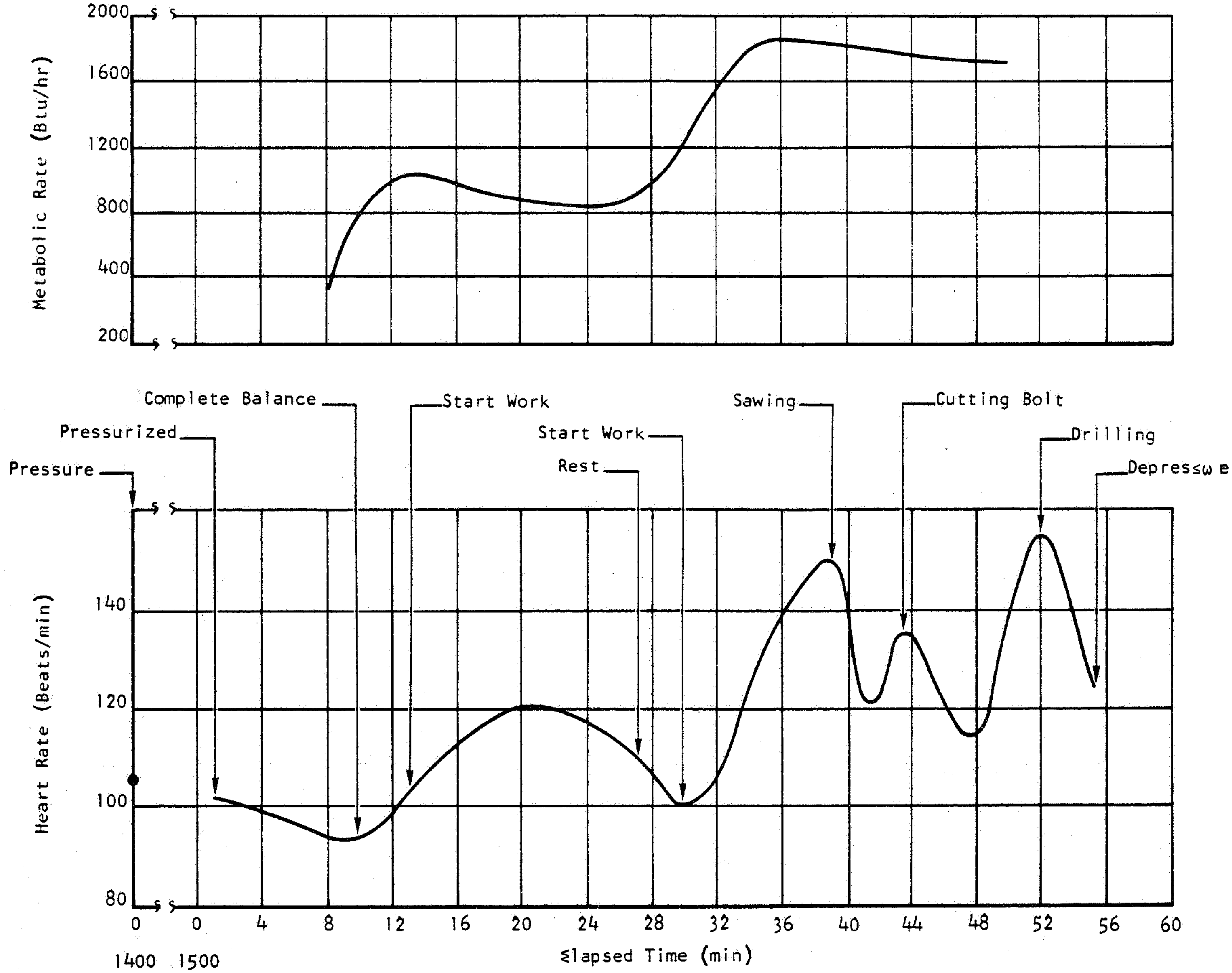


Figure 7-17. Assembly and Erection of an Inflatable Module, Tests 1.7.1.6, 1.7.3.6, and 1.7.5.6



A-28393

Figure 7-18. Physiological Data for Suspension Simulation Maintenance Test

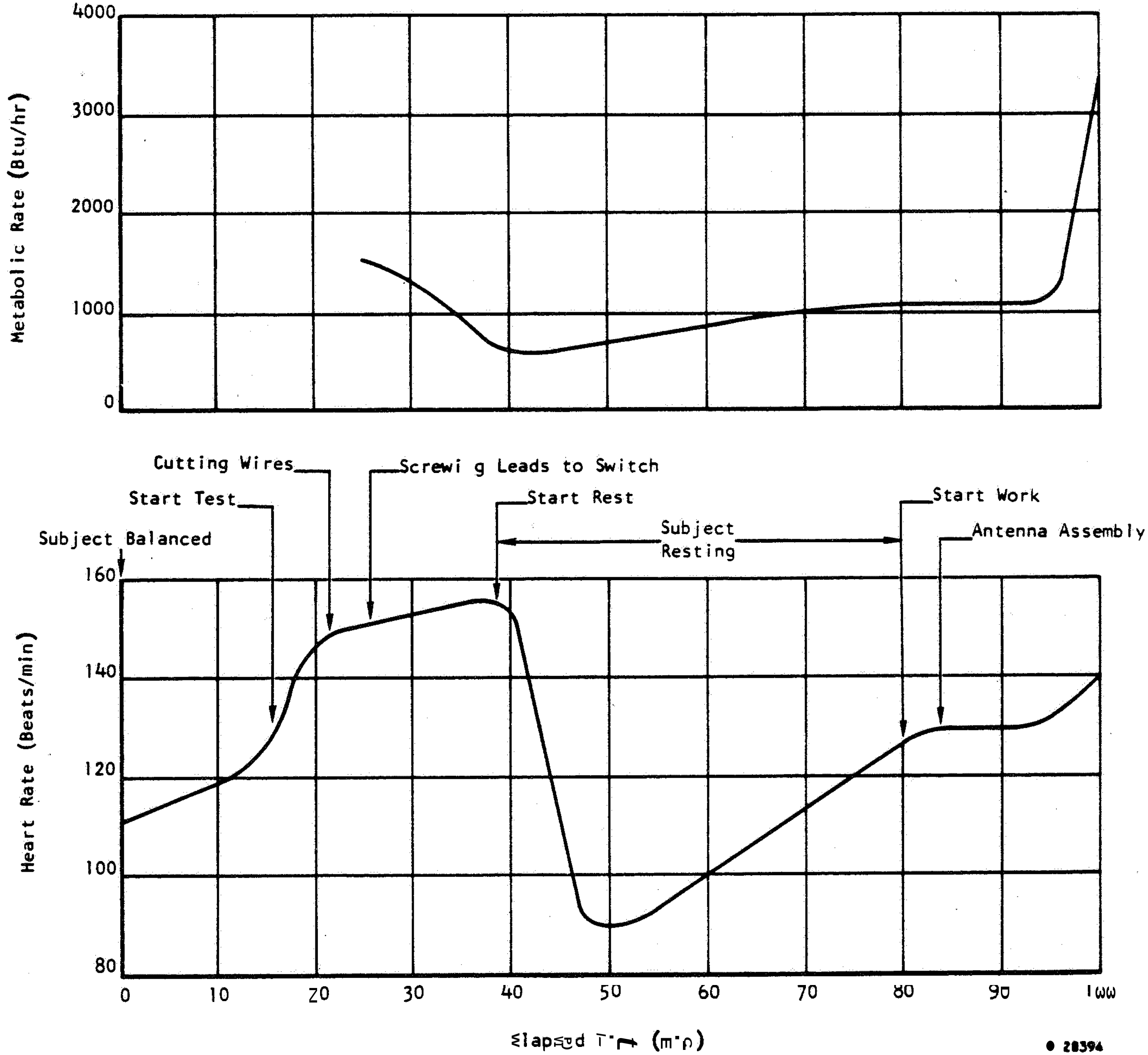


Figure 7-19 Physiological Data for Suspension Simulation Maintenance and Antenna

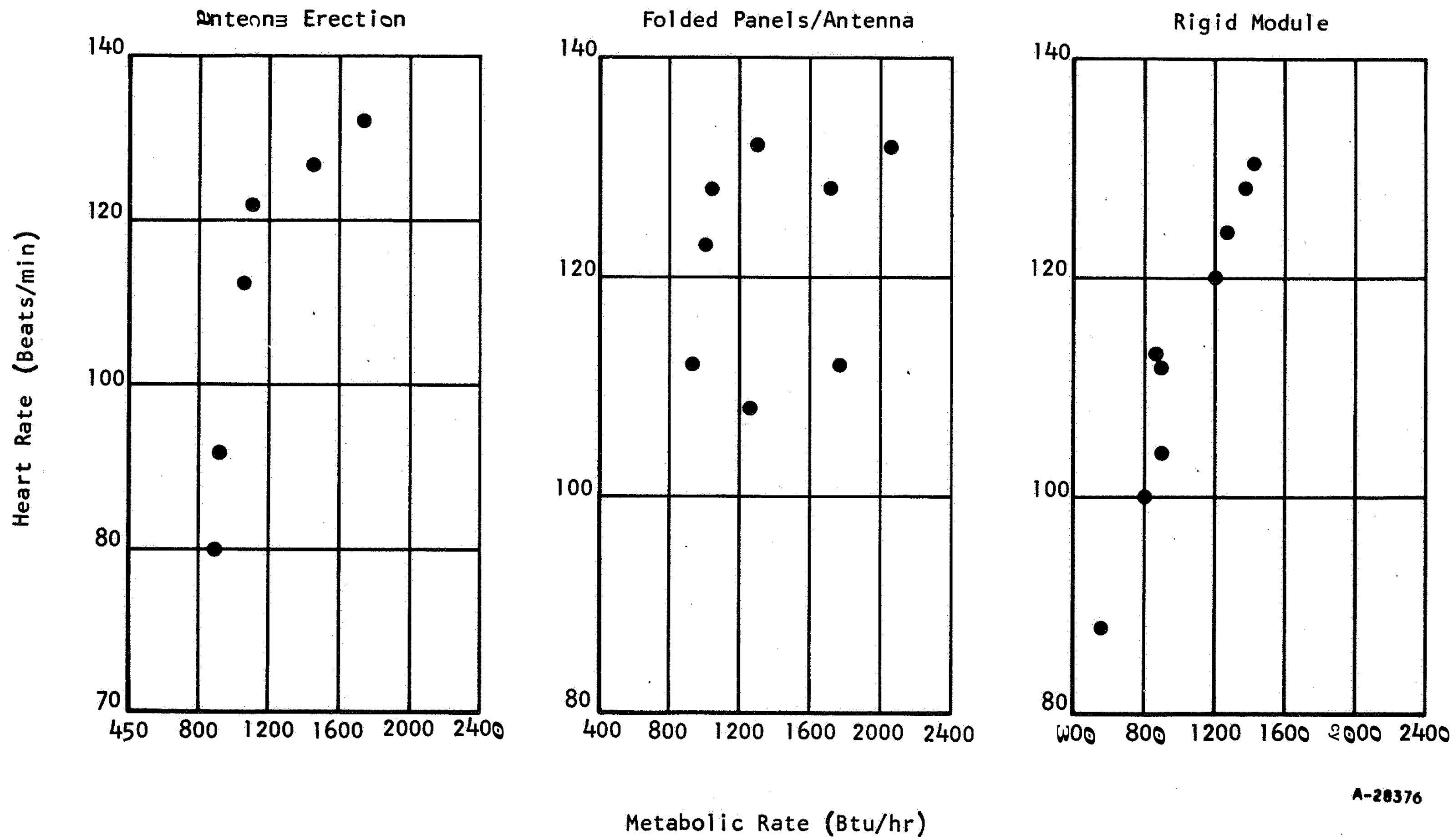


Figure 7-20. Heart Rate vs Metabolic Rate

SECTION 8

GENERAL CONCLUSIONS

Some of the most general conclusions derived from this study are as follows:

a. The extent of man's capabilities to perform maintenance and assembly tasks in weightlessness is much greater than had been originally anticipated. With appropriately designed tools, restraint devices, locomotion aids, and task sequences it appears that any foreseeable manual task can be accomplished in weightlessness. This observation must be tempered with a complete lack of knowledge on the problems of mass manipulation. In addition, great emphasis must be attached to proper design of EVA hardware.

b. Weightless simulation at low limb and body velocities appears to be better accomplished by neutral buoyancy simulation than by the six-degrees-of-freedom simulator.

c. Performance data, even during these exploratory studies, become systematic when organized by the provisional task taxonomy developed for this program.

d. Average metabolic rates were on the order of 1500 to 1600 Btu hr with peak values at 2000 Btu hr. These peak values were infrequent and of short duration.

e. Heart rates were similar to Gemini XII EVA data; i.e., 140 to 150 bpm beats/min.

f. Optimal restraints systems will apparently use the human skeletal structure as part of the restraint system.

g. It appears unlikely that a single restraint system can be designed that is best for all tasks. Some restraint concepts are best for working in place, while others become optimal when location changes of even a minor nature are required.

h. A number of hardware items need development for the satisfactory conduction of manual or semimanual EVA work. These included:

Restraint devices

Manual and power tools

Easily manipulated, positively locking fasteners

Apparatus for handling and presenting tools, components, and parts

i. Good EVA in terms of both dexterity and force is dependent on stability and appropriate positioning of the worker.

j. Detailed "hand-by-hand" task analyses must be conducted in developing procedures for any EVA or IVA in large volumes.

k. Manual construction of large rigid or inflatable structures such as antennas or shelters can be accomplished manually in weightlessness.

l. Complete and detailed simulation is required to check out all work projected for the weightless environment.

REFERENCES

1. Graveline, D. E, and G. W. Barnard, Aerospace Medicine 32:726, 1961.

2. Graybiel, A., and B. Clark, Aerospace Medicine, 32:181, 1961.

3. Peterson, L. H, Proceedings of the Second Symposium - Underwater Physiology, NAS-NRC Publication 1181, Washington, 1963, pp 267-270.

4. Irving, L, P. F. Scholander, and S. N. Grinell, American Journal of Physiology, 135:557, 1942.

5. Olsen, C. R., D. D. Fanestil, and P. F. Scholander, Journal of Applied Physiology, 17:461, 1962.

6. Craig, A. B., Jr., Journal of Applied Physiology, 18:854, 1963.

7. Wolf, S., Trans. Am. Clin. Climat. Assoc., 76:192, 1964.

8. Scholander, P. F., H. T. Hammel, D. H LeMessurier, E. Hemningsen, and W. Garey, Journal of Applied Physiology 17:184, 1962.

9. Irving, L., Journal of Applied Physiology, 18:489, 1963.

10. Stolurow, Laurence M, "A Taxonomy of Learning Task Characteristics," AMRL-TDR-64-2, 1964.

11. Melton, Arthur W., Categories of Human Learning, Academic Press, New York, 1962.

12. Smith, Karl U, "Cybernetic Theory and Analysis of Learning," in Bilodeau, Edward A. (ed.), Acquisition of Skill, Academic Press, New York, 1966.

13. Fleishman, E. A., "Development of a Behavior Taxonomy for Describing Human Tasks," Journal of Applied Psychology, Vol. 51, 1967, 1-10.

14. Fleishman, E. A, and W. E. Hempel, "A Factor Analysis of Dexterity Tests," Personal Psychology, 1954, 7, 35-32. (a).

15. Fleishman, E. A., W. E. and Hempel, "Changes in Factor Structure of a Complex Psychomotor Test as a Function of Practice," Psychometrika, 1954, 18, 239-252..

16. Fleishman, E. A., The Structure and Measurement of Physical Fitness, Prentiss-Hall, Inc., Englewood Cliffs, New Jersey, 1964.

17. Fleishman, E. A, "'Comments on Professor Jones'" in Bilodeau, Edward A. (ed.), Acquisition of Skill, Academic Press, New York, 1966.

a

18. Laban, Rudolf and F. C. Lawrence, Effort, Macdonald and Evans, London, 1947.

19. Hoerner, S. F., Fluid-Dynamic Drag, Published by the author, 148 Busteed Drive, Midland Park, New Jersey, 1958.

20. Schmitt, T. J., "Wind-Tunnel Investigation at Air Loads on Human Beings," Report 892 (Aero 858), David W. Taylor Model Basin, Navy Dept., January 1954.

21. Trout, O. F., Jr., H. L. Loats, Jr., and Mattingly, "A Water-Immersion Techniaue for the Study of Mobility of a Pressure-Suited Subject Under Balanced-Gravity Condition," NASA TND-3054, January 1966.

22. Brouha, Journal of Applied Physiology, Vol. 18, No. 6, 1963.

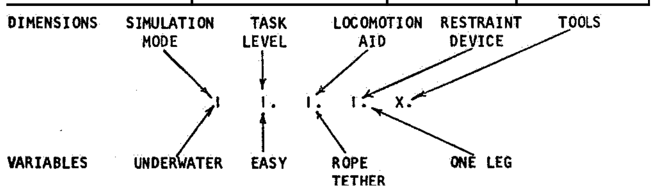
APPENDIX A

TEST CODE NUMBERS

TABLE A-1

TEST CODE AND DESCRIPTION

SIMULATION MODE	TASKS TYPE AND LEVEL	LOCOMOTION AID	RESTRAINT DEVICE	TOOLS
1. Underwater 2. One-g 3. Suspension simulation	1. Easy 2. Difficult 3. Hard Large Modules Erection Tests 4. Beams (antenna) 5. Folding panels (antenna face) 6. Two rigid modules 7. Two inflatable modules	1. Rope tether 2. Hand rail 3. Hand hold 4. Taut rope 5. Rigid pole (fixed one end only)	1. One Leg 2. Two Leg 3. Three Leg 4. Cage 5. Foot With Strap Tether 6. Gemini XII Type Straps	1. Hammer 2. Clamps 3. Saw 4. Punch 5. Wrenches 6. Screwdriver 7. Pliers 8. Hand Drill



UNDERWATER MAINTENANCE TEST CODES

	CODE	XX1.1.	XX2.2.	XX3.3.	XX4.4.	XX5.5
	RESTRAINT	One Leg	Two Leg	Three Leg	Cage	Foot Strap
	LOCOMOTION AID	Rope Tether	Hand Rail	Hand Hold	Taut Rope	Rigid Pole
UNDERWATER SUITED	1.1.XX Easy	1.1.1.1.	1.1.2.2.	1.1.3.3.	1.1.4.4.	1.1.5.5.
	1.2.XX Difficult	1.2.1.1.	1.2.2.2.	1.2.3.3.	1.2.4.4.	1.2.5.5.
	1.3.XX Hard	1.3.2.2.	1.3.3.3.	1.3.3.3.	1.3.4.4.	1.3.5.5.

ONE-G MAINTENANCE TEST CODES

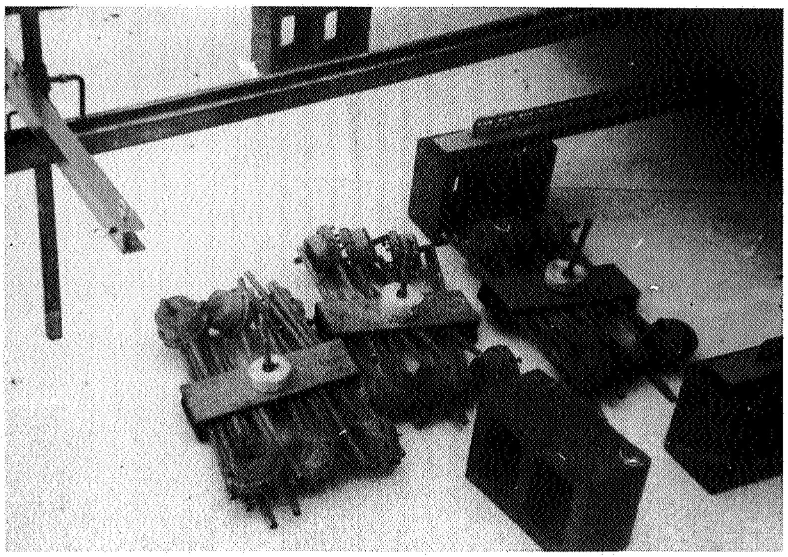
	CODE	XX0.1.	XX0.2.
	RESTRAINT	One Leg	Two Leg
	LOCOMOTION AID	NONE	NONE
FULL GRAVITY SUITED	2.1.XX Easy	2.1.0.1.	2.1.0.2.
	2.2.XX Difficult	2.2.0.1.	2.2.0.2.
	2.3.XX Hard	2.3.0.1.	2.3.0.2.

MISCELLANEOUS MAINTENANCE TEST CODES

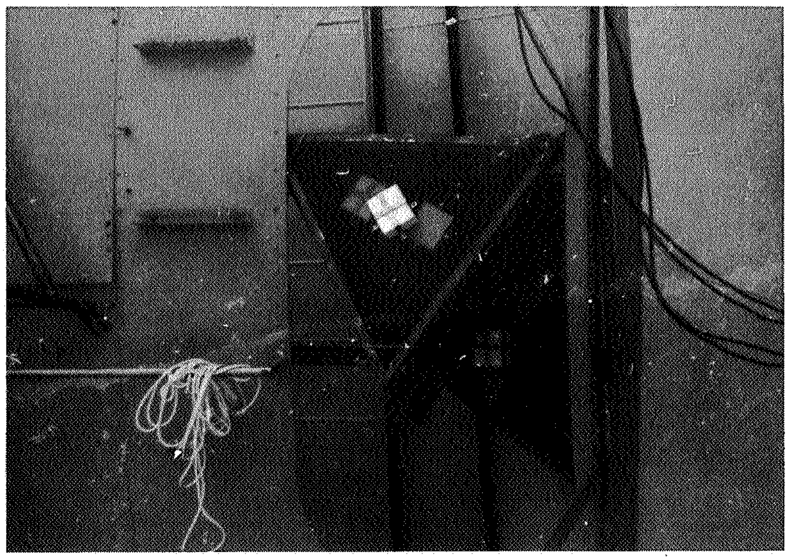
TEST CODE	DESCRIPTION
1.3.3.6.	Underwater, Hard, Hand Hold, Gemini XII
3.1.0.6. 3.2.0.6. 3.3.0.6.	Six-degrees-of-freedom Easy, Difficult, Hard Composite, No Locomotion Aid, Gemini XII Type Strap Restraint

APPENDIX B

ILLUSTRATIONS OF EVA WORK



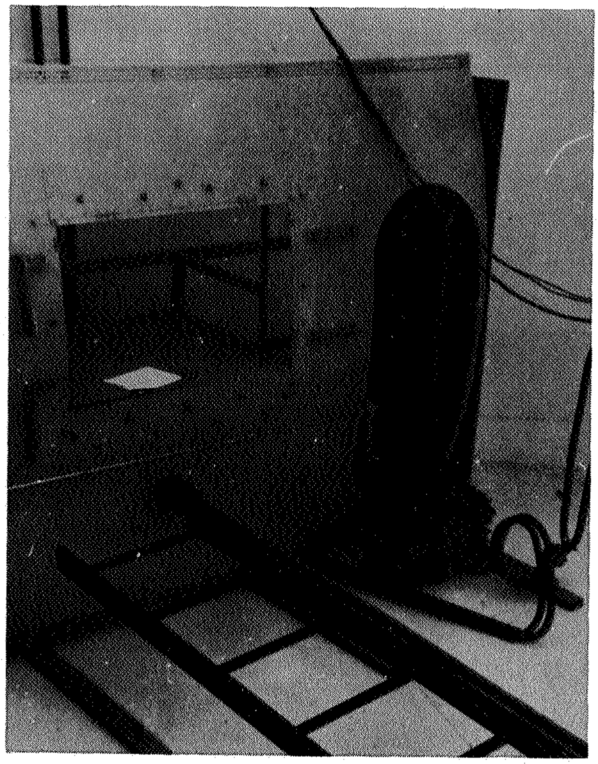
PACKAGED ANTENNA BEAMS AND JOINTS



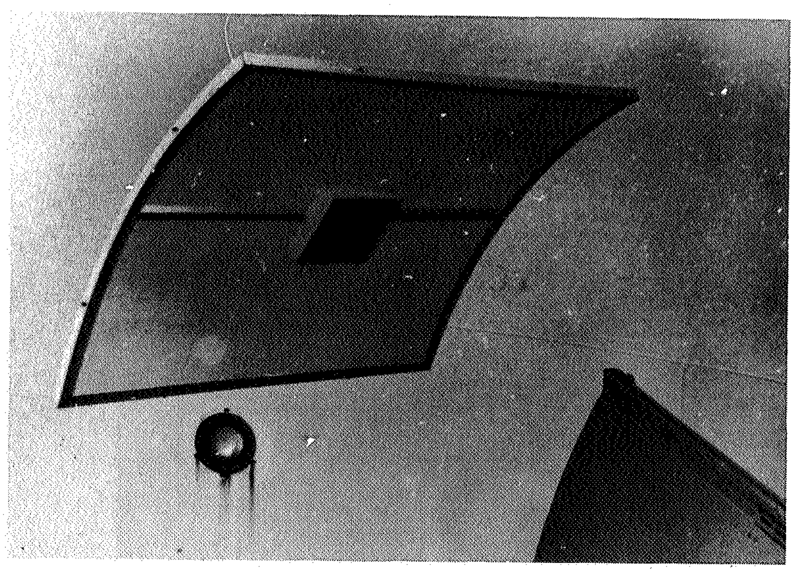
PACMGED ANTENNA PANELS

F-7343

Figure B-1



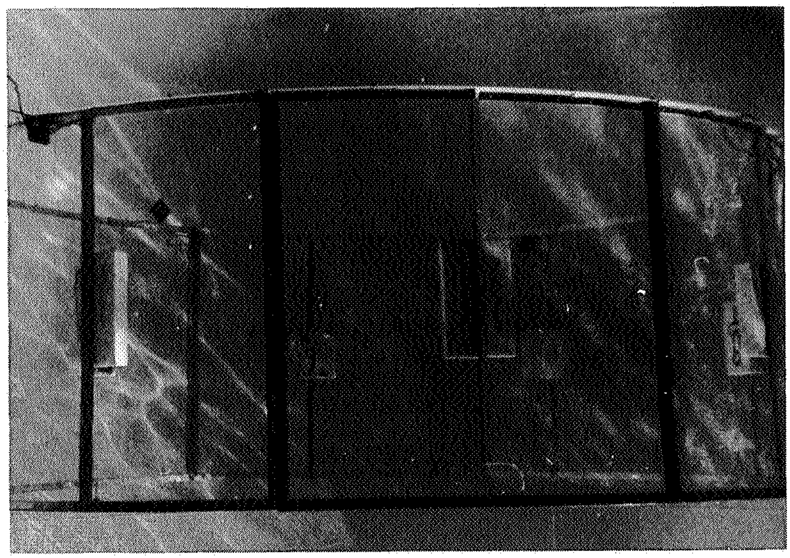
PACKAGED INFLATABLE MODULES
(AT BOTTOM OF HATCH)



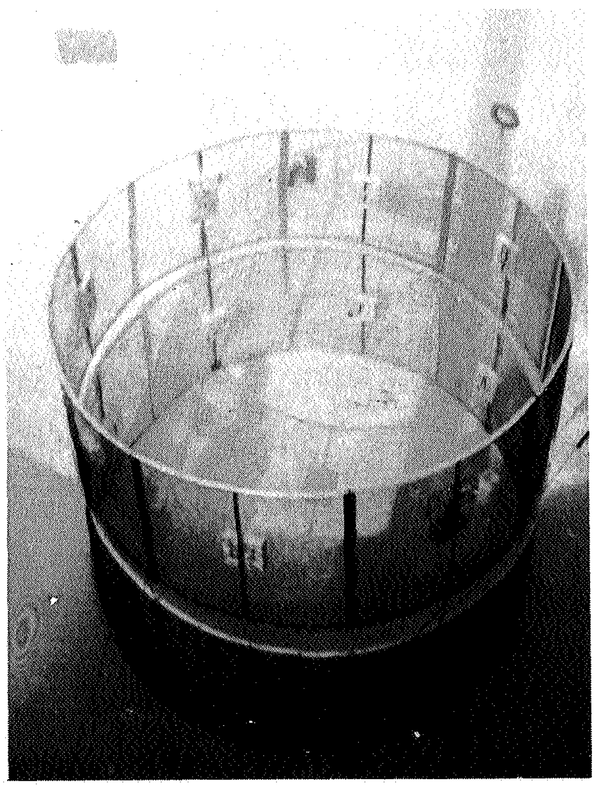
F-7344

NEUTRALLY BUOYANT PANEL FOR LARGE RIGID MODULES

Figure B-2



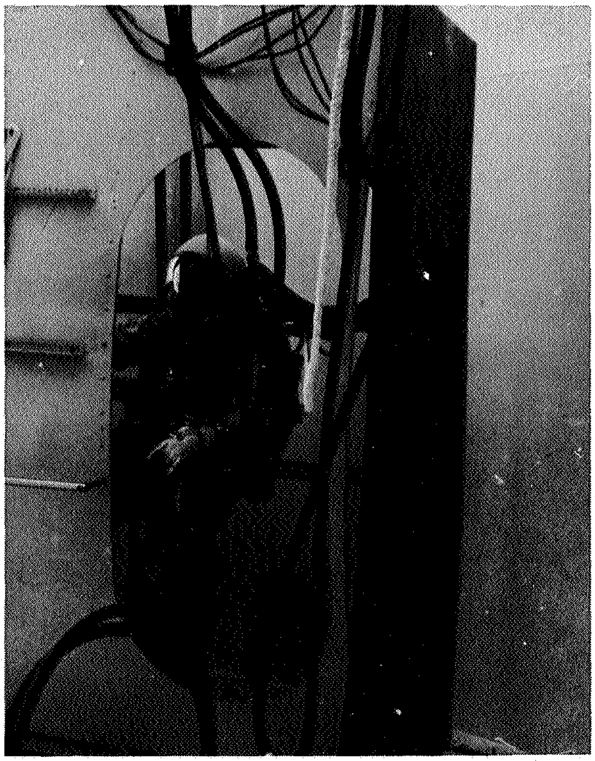
NEUTRALLY BUOYANT LARGE RIGID MODULE, ASSEMBLED



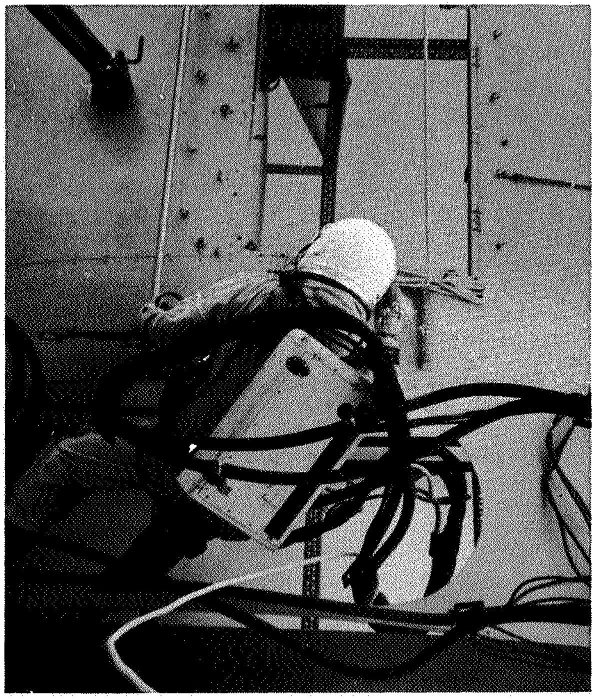
LARGE RIGID MODULE ASSEMBLED BUT NOT CONNECTED

F-7345

Figure B-3



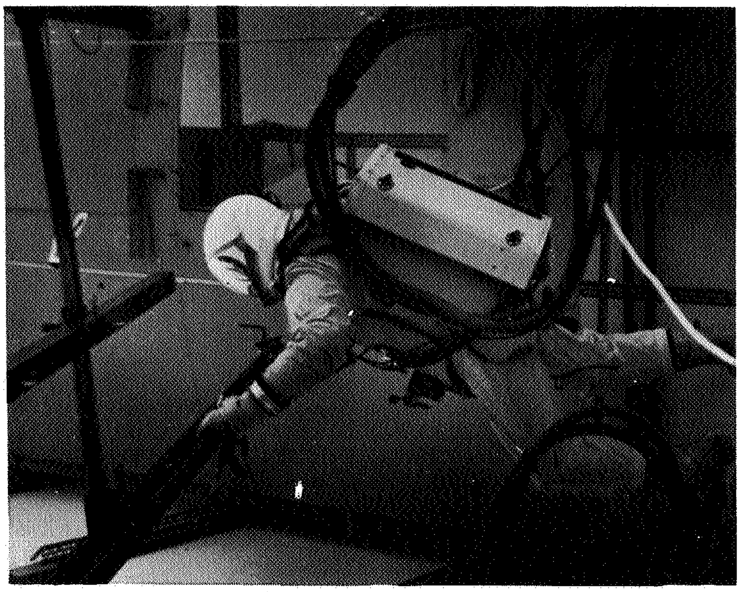
SUBJECT IN HATCH, READY TO BEGIN TEST



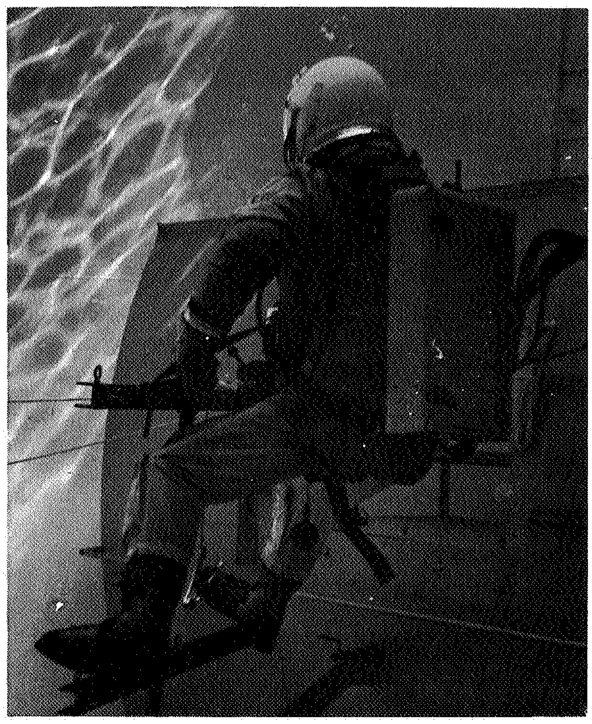
F-7346

SUBJECT LEAVING HATCH ONTO HANDRAIL

Figure B-4



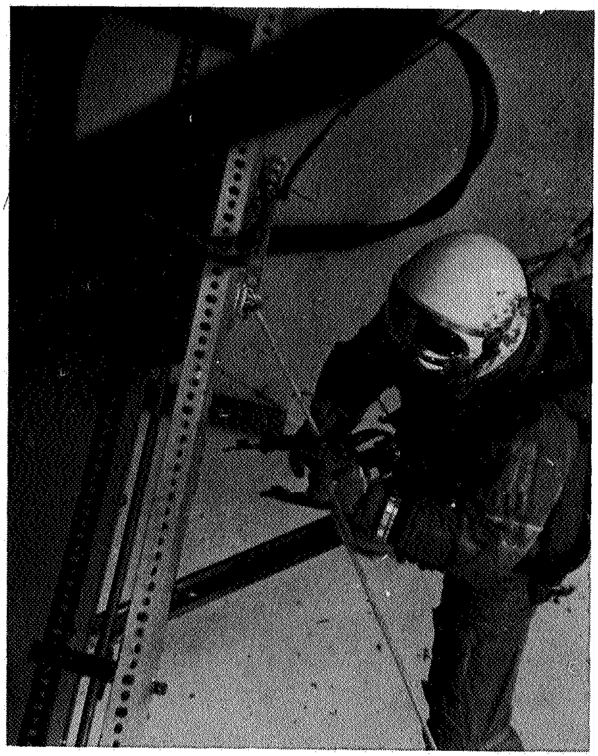
"CRAB" LOCOMOTION ON MAINTENANCE BOOM



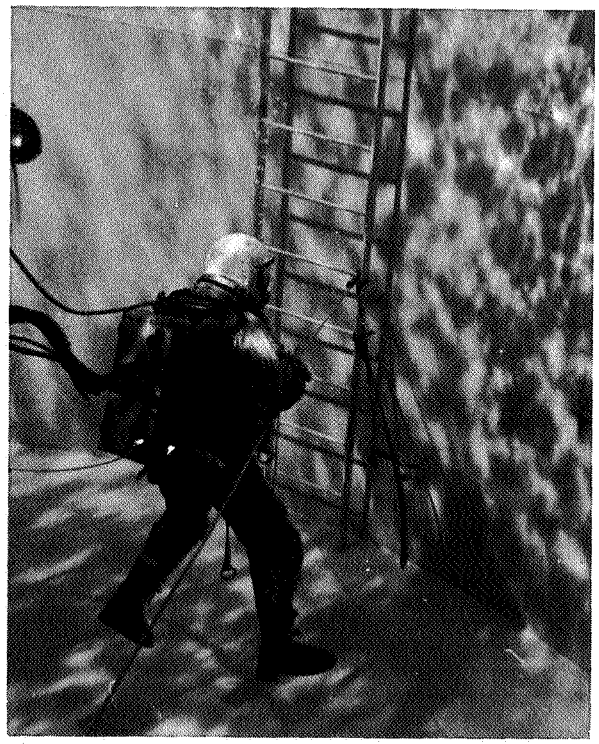
F-7347

SUBJECT GETTING LINEMANS POSITION ON "T" RESTRAINT

Figure **B-5**

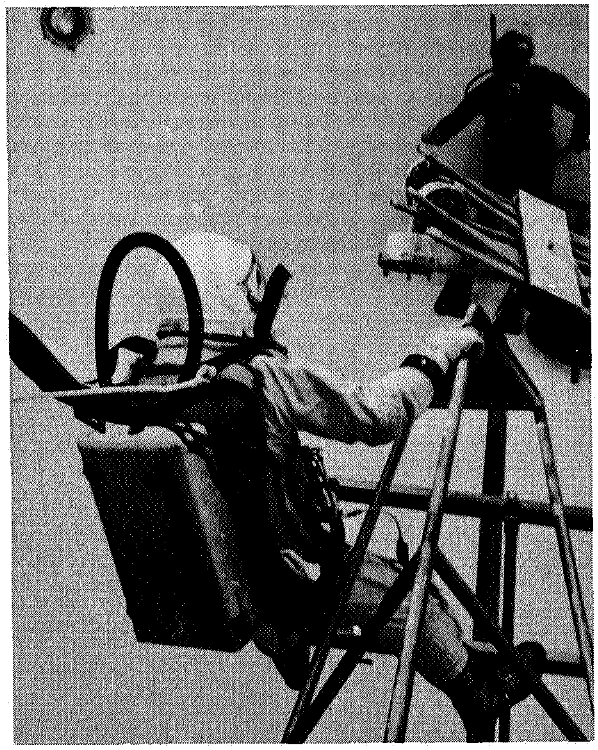


SUBJECT SECURING STRAP RESTRAINT ON TAUT ROPE LOCOMOTION AID



TRAVERSING, TAUT ROPE F-7348

Figure **B-6**

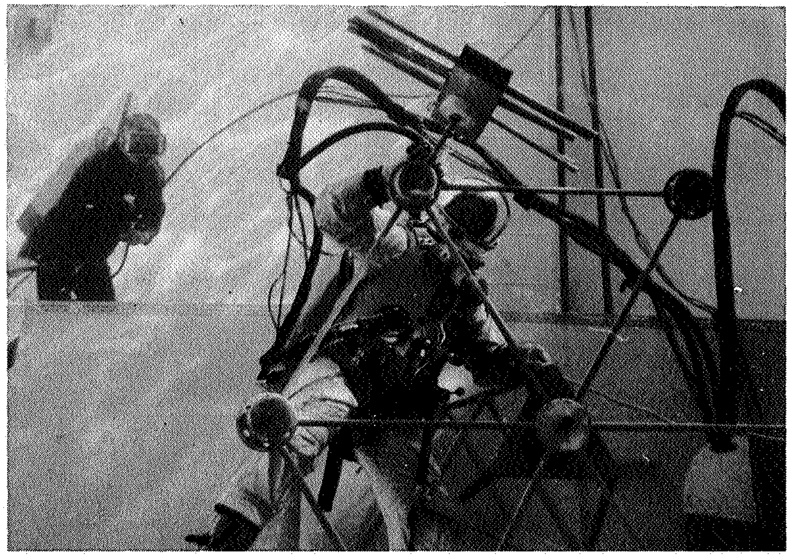


TRAVERSING, ANTENNA BOOM

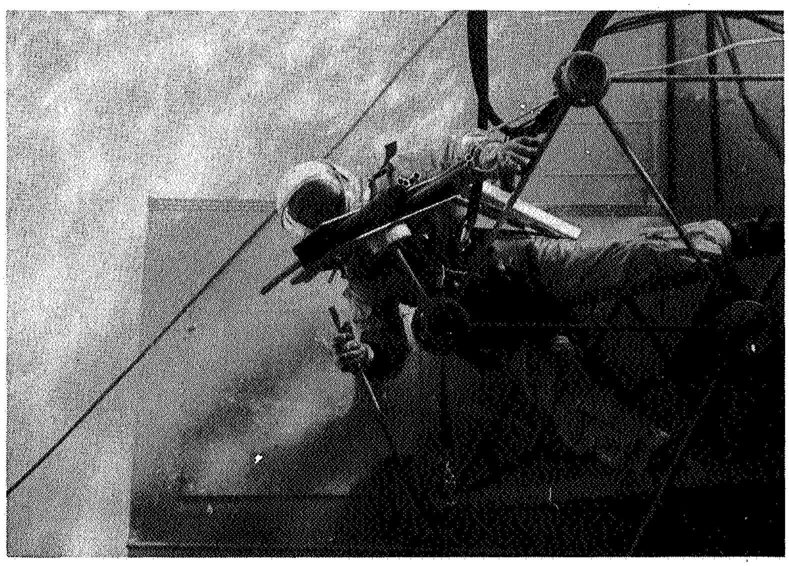
F-7349

BEGINNING TRAVERSE WITH ANTENNA PACKAGE

Figure B-7



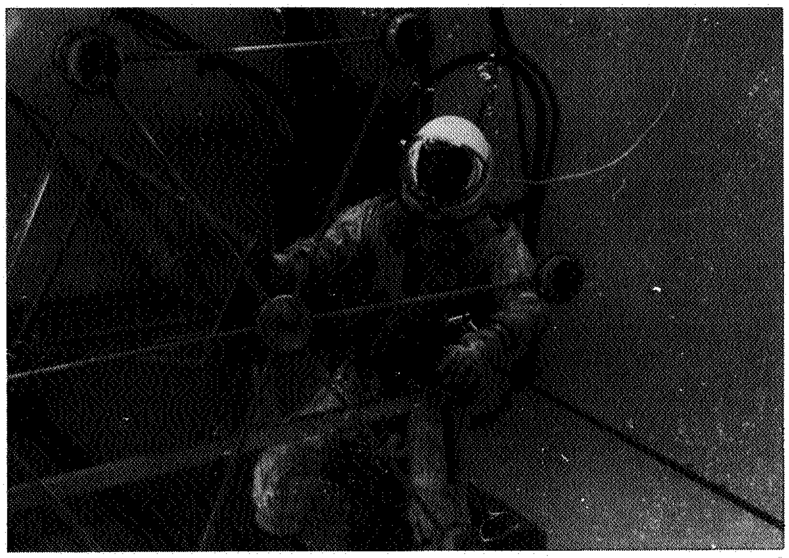
ANTENNA ASSEMBLY FROM REAR



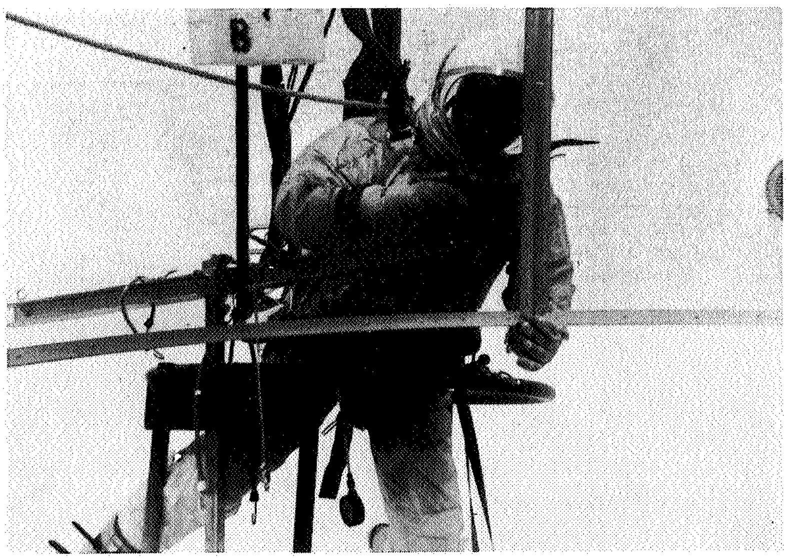
ANTENNA ASSEMBLY FROM END

F-7350

Figure B-8



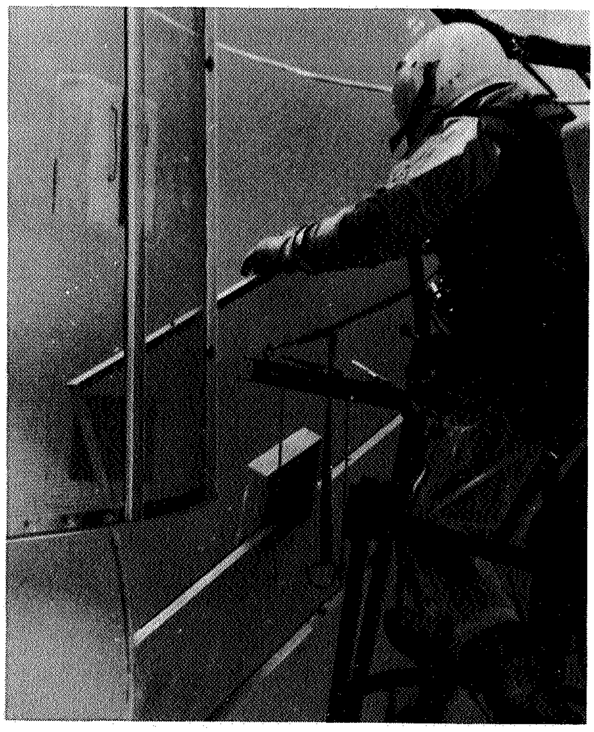
LEAVING RESTRAINT AID TO WORK LOW ON ANTENNA



RIGID MODULE SECTION FITTING USING CAGE RESTRAINT

F-7351

Figure *B-9*

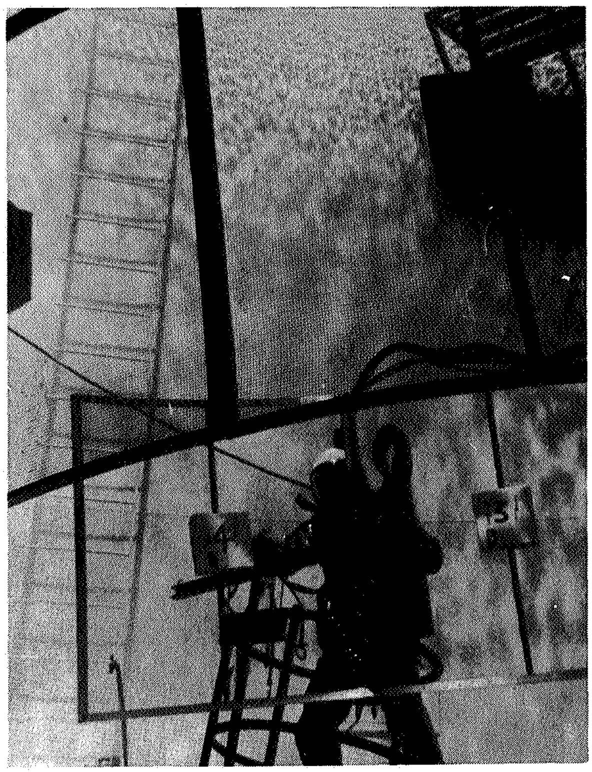


PANEL PLACEMENT FROM CAGE RESTRAINT

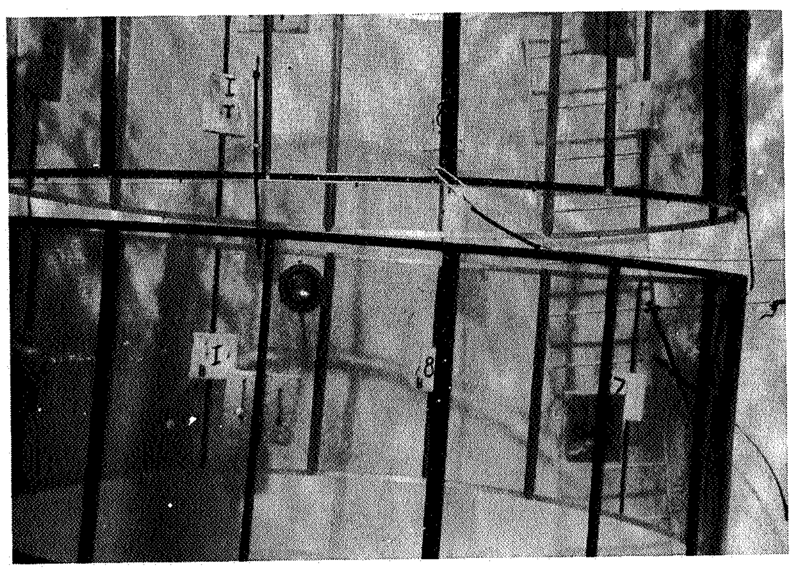
F-7352

SUBJECT ASSEMBLING SECOND RIGID
MODULE AS SEEN FROM TOP OF TANK

Figure B-10



CAGE RESTRAINT "BOUNCE" ON MAINTENANCE BOOM



F-7353

TWO NEUTRALLY BUOYANT MODULES BEFORE BOLTING TOGETHER

Figure B-11

LINEMAN'S POSITION WHILE CONNECTING TWO MODULES

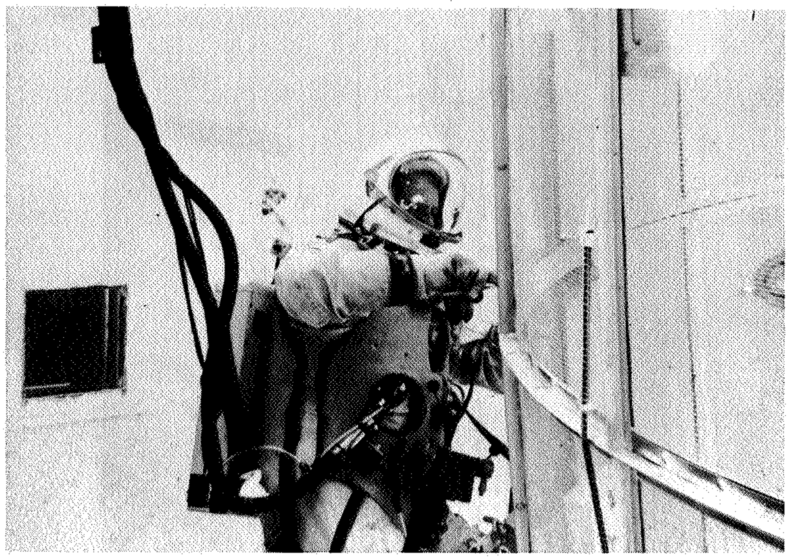
SUBJECT HAVING POSITIONAL CONTROL PROBLEM F-7354

Figure B-12

MOVING MODULES AROUND AND BOLTING TOGETHER

CLAMPING MODULES PRIOR TO BOLTING F-735'5

Figure **B-13**

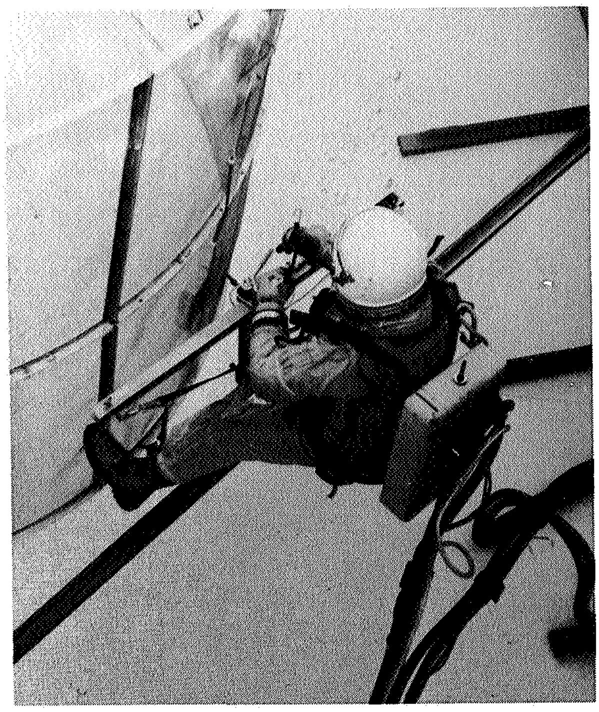


BOLTING TWO RIGID MODULES TOGETHER, "LINEMAN" VARIATION

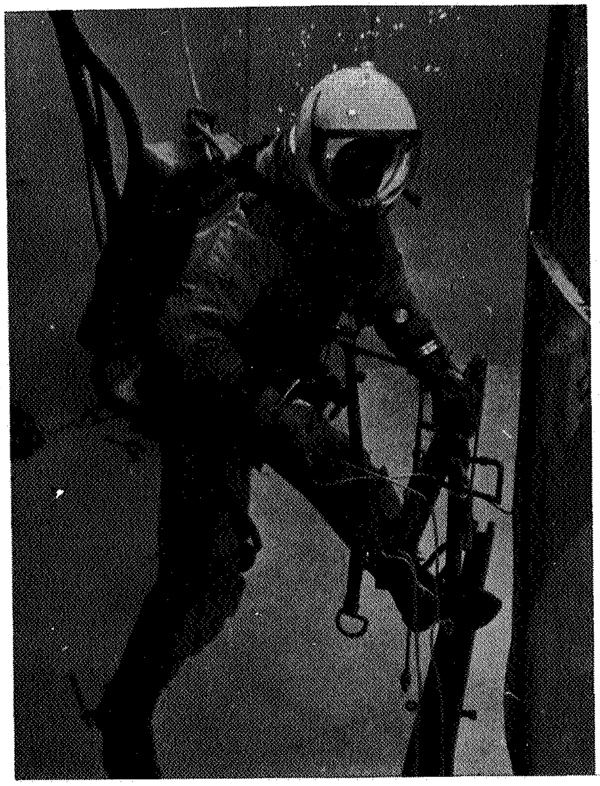
F-7356

RESTING DURING ASSEMBLY

Figure B-14



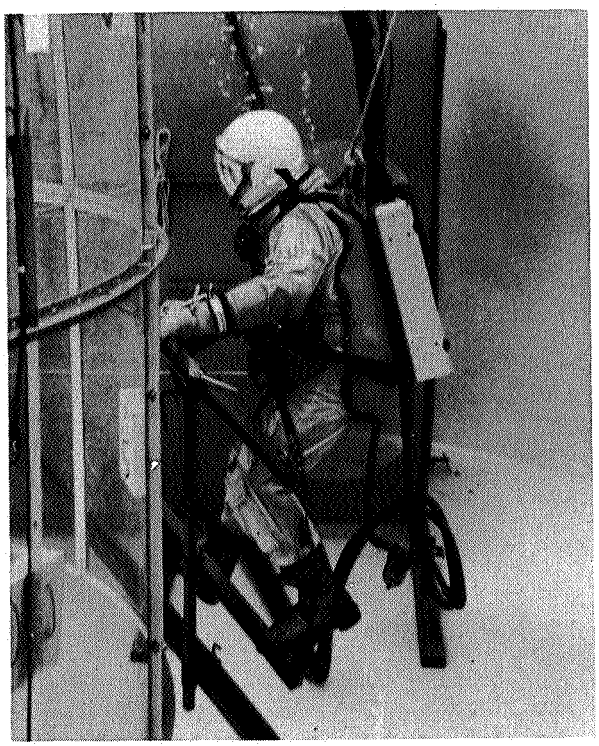
LINEMAN'S POSITION DURING MODULE MATING



LIGHT LINE DIFFICULTY F-7357

Figure B-15

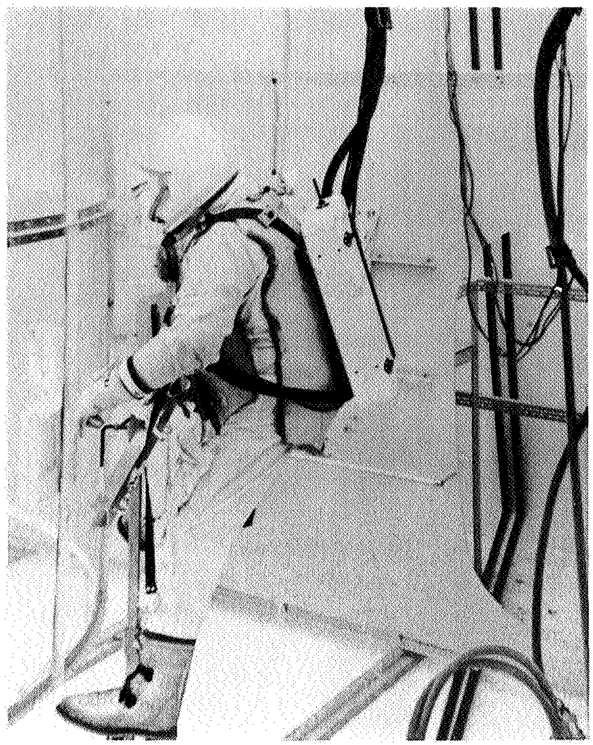
FALLING OUT OF LINEMAN POSITION CAUSED BY "PLAY" AND "BOUNCE" IN MAINTENANCE BOOM AND "T" RESTRAINT



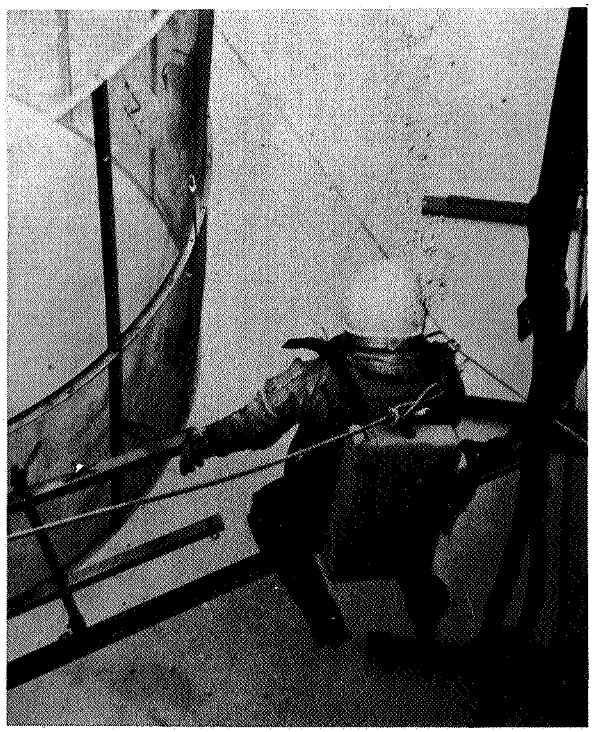
F-7358

MOVING FROM LINEMAN'S POSITION TO A VARIATION

Figure 8-16



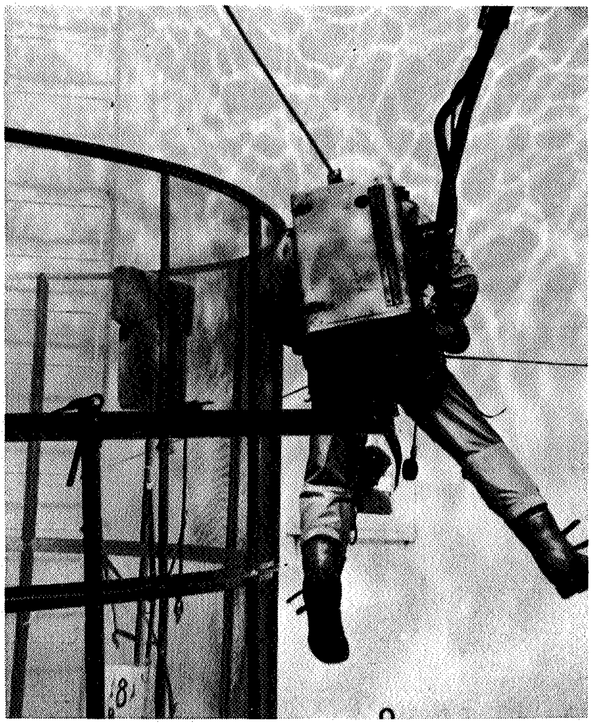
SHORT STRAP LINEMANS POSITION



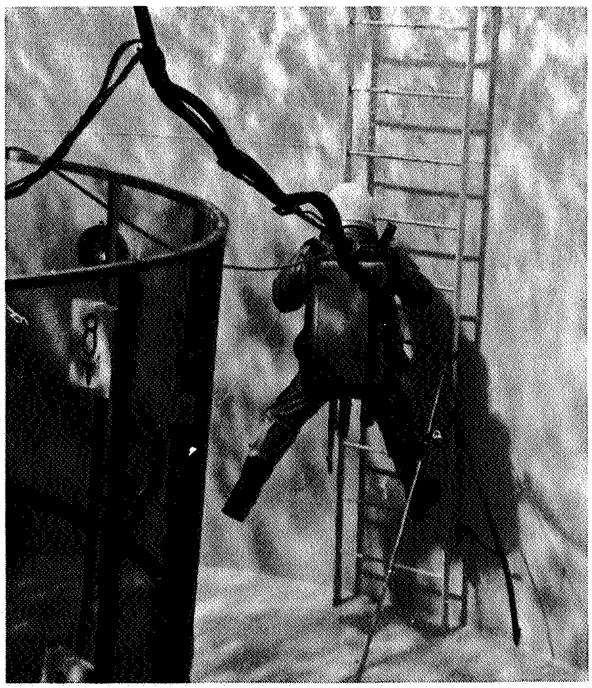
F-7359

SUBJECT ATTACHED TO TAUT ROPE
BY EYE OF RESTRAINT STRAP

Figure B-17



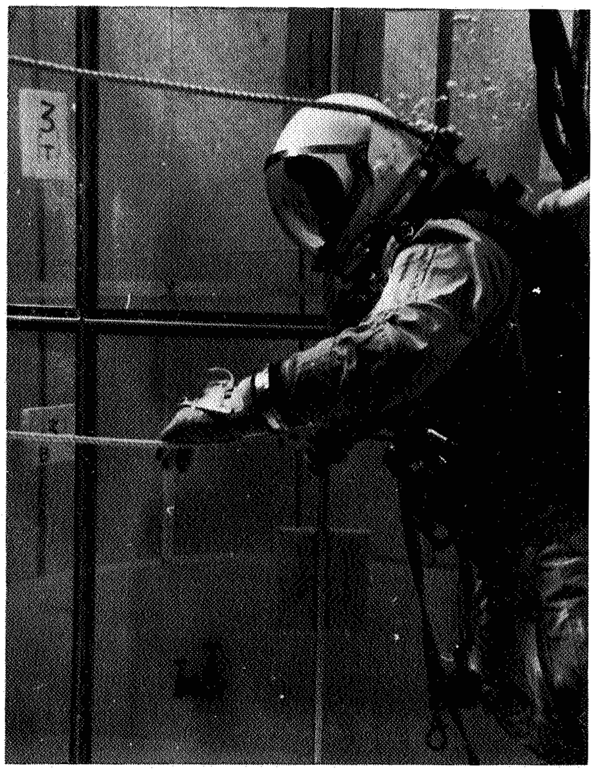
MOVING ON TAUT ROPE USING BOTH HANDS



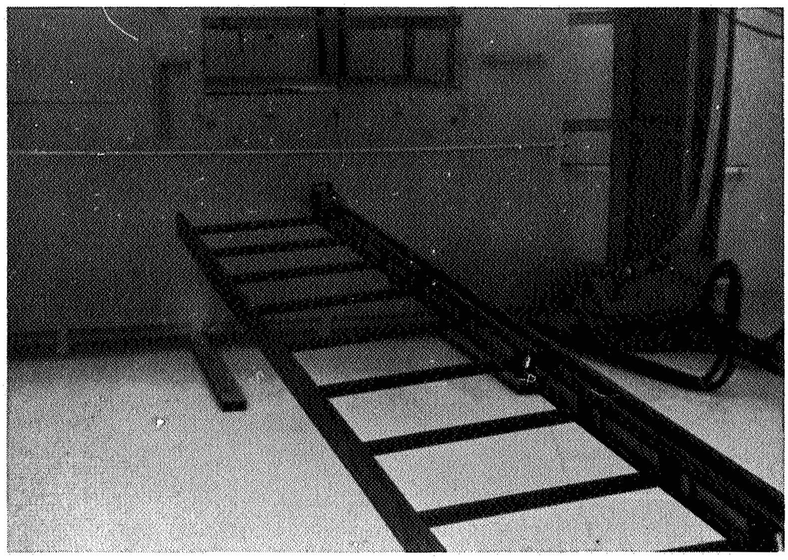
SUBJECT PREPARING ROPE-PULLEY TO MOVE TWO RIGID MODULES

F-7360

Figure B-18



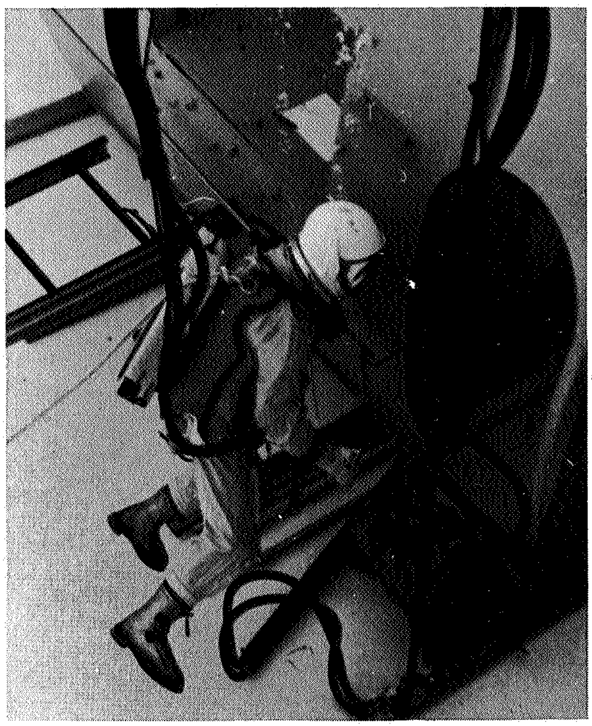
SUBJECT RETURNING ALONG TAUT ROPE FROM LADDER



F-7361

LADDER ATTACHED TO MAINTENANCE BOOM
FOR INFLATABLE MODULE TEST

Figure B-19

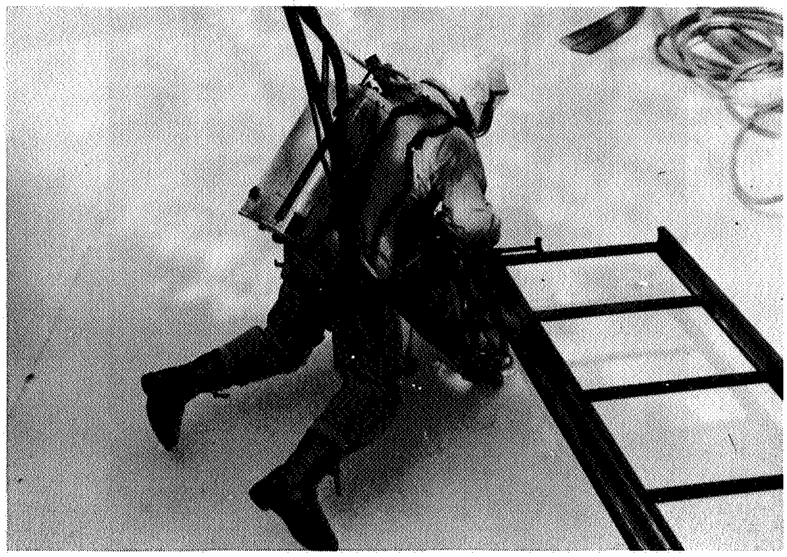


SUBJECT PREPARING TO MOVE INFLATABLE MODULE PACKAGE

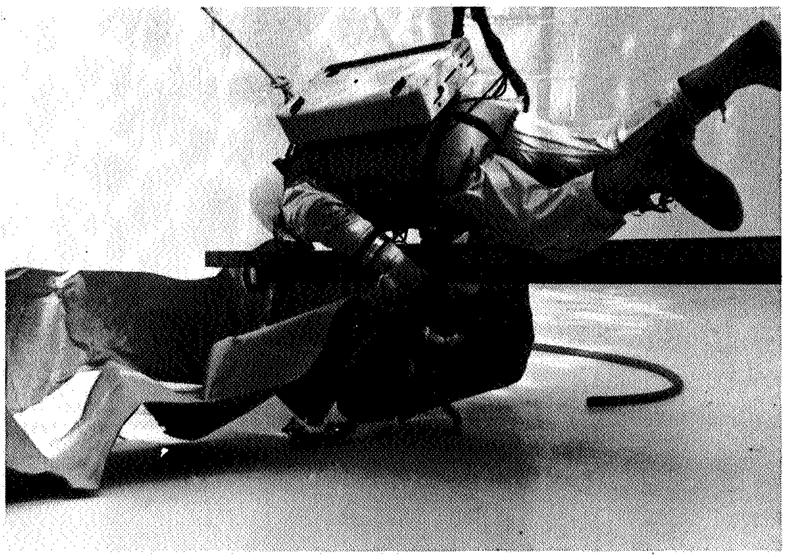
"CRAB" TRAVERSE WITH PACKAGE

F-7362

Figure B-20



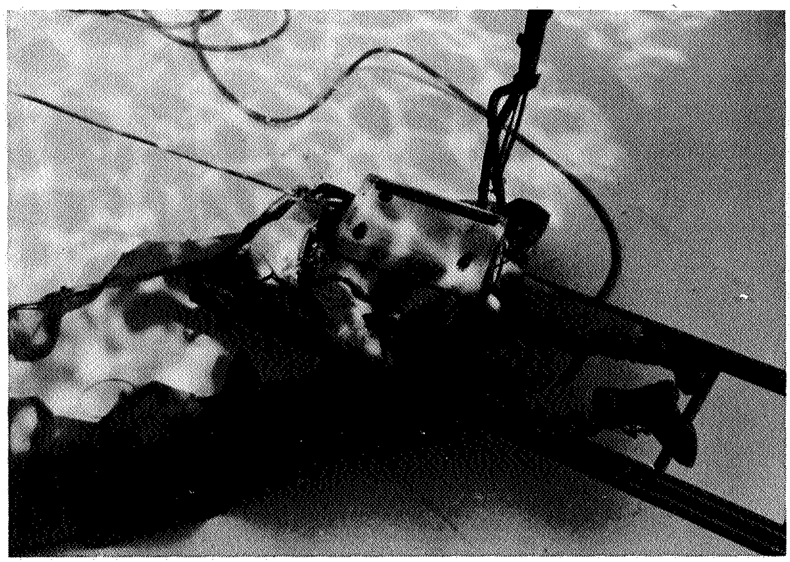
ATTACHING STRAP RESTRAINT WITH PACKAGE IN HAND



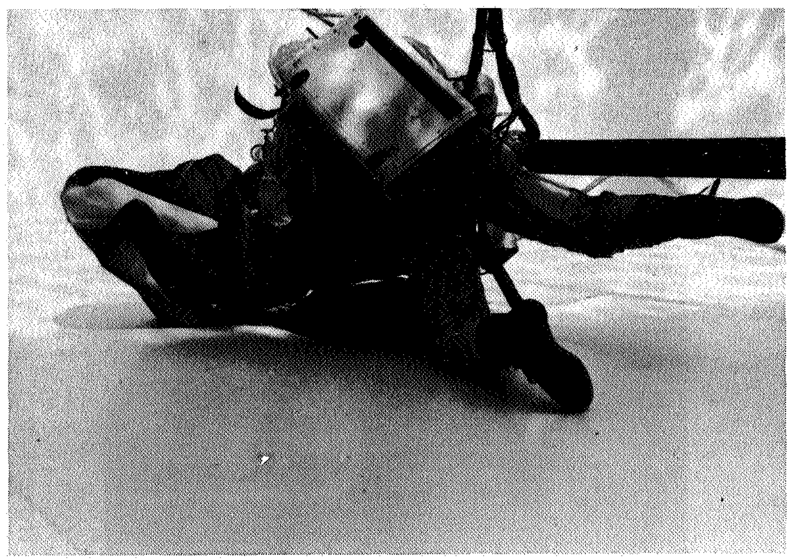
F-7363

UNFOLDING INFLATABLE MODULE

Figure B-21



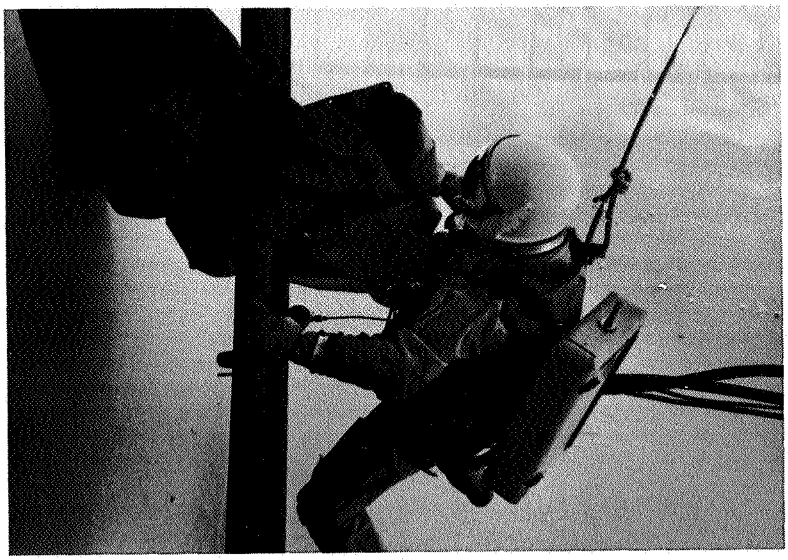
TOP VIEW OF UNFOLDING TASK



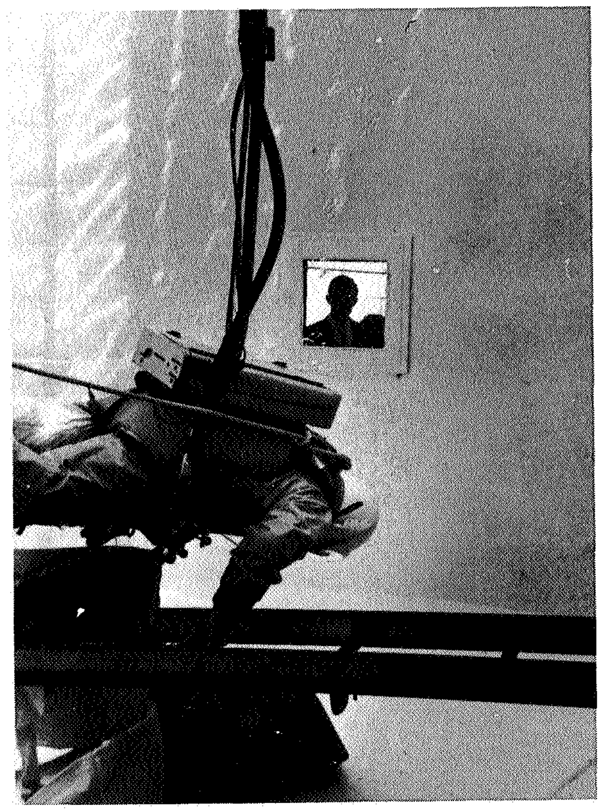
F-7364

SUBJECT OUT OF CONTROL, HAS PULLED
SELF TO BOTTOM OF TANK

Figure B-22



MOVING MODULE BACK TOWARD SPACECRAFT MOCKUP OVER BOOM



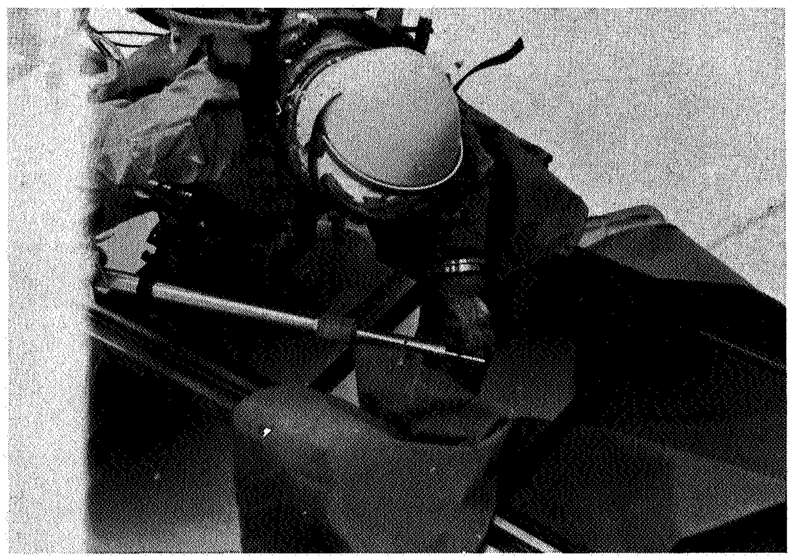
F-7365

MOVING MODULE BACK TOWARD SPACECRAFT MOCKUP OVER BOOM

Figure 8-23

1

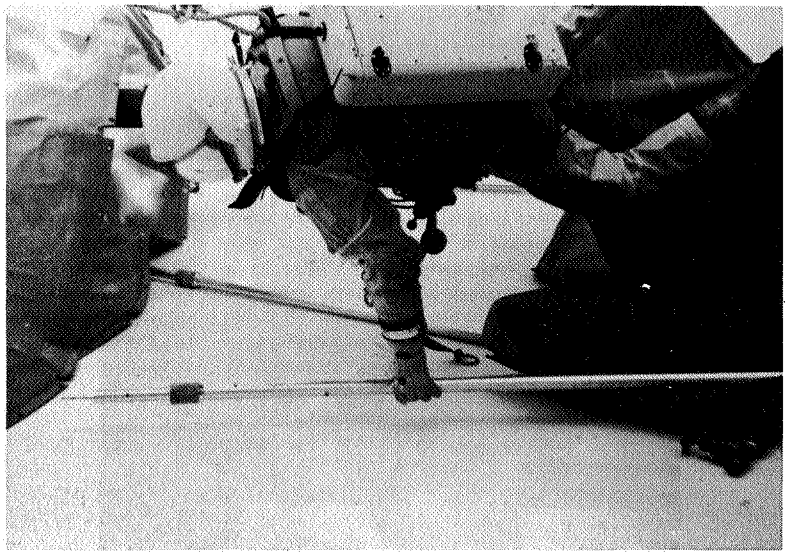
POSITIONING MODULE FOR SECURING TO SPACECRAFT MOCKUP



ATTACHING TELESCOPING RODS

F-7366

Figure 8-24

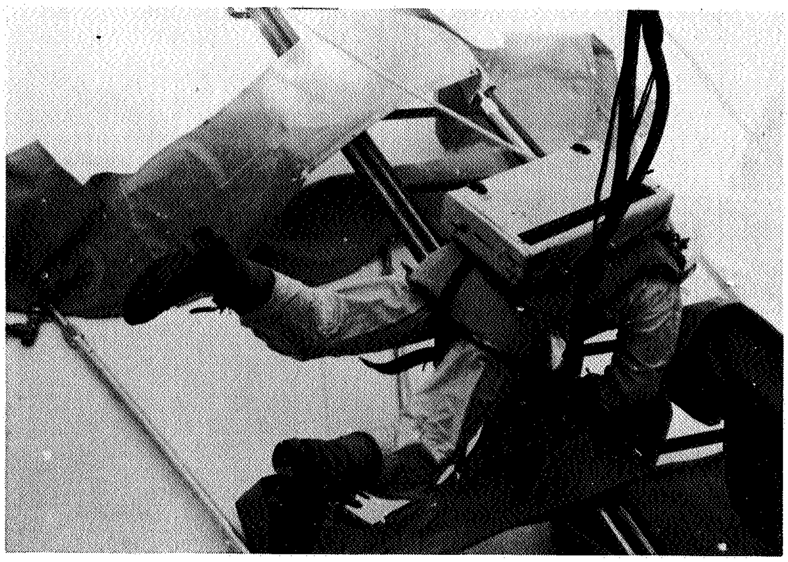


ATTACHING TELESCOPING RODS

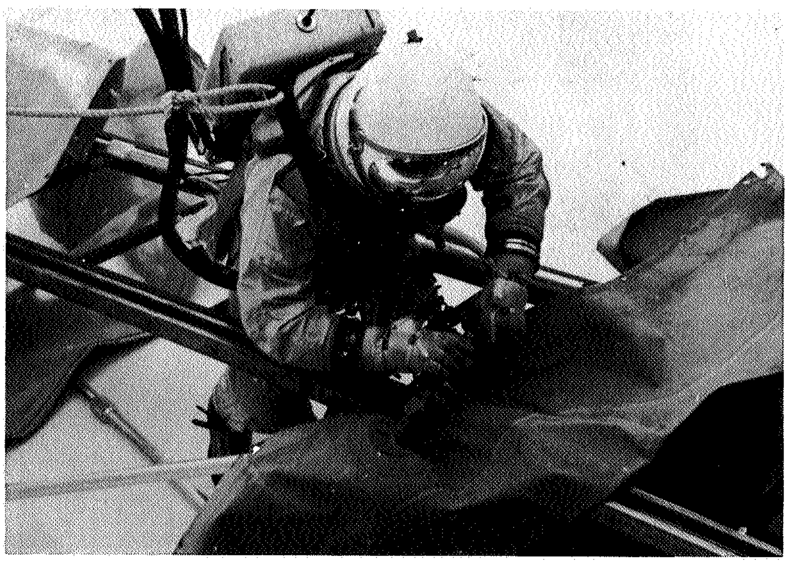
SUBJECT TURNING MODULE TO FINO ATTACHING POINT

F-7367

Figure B-25



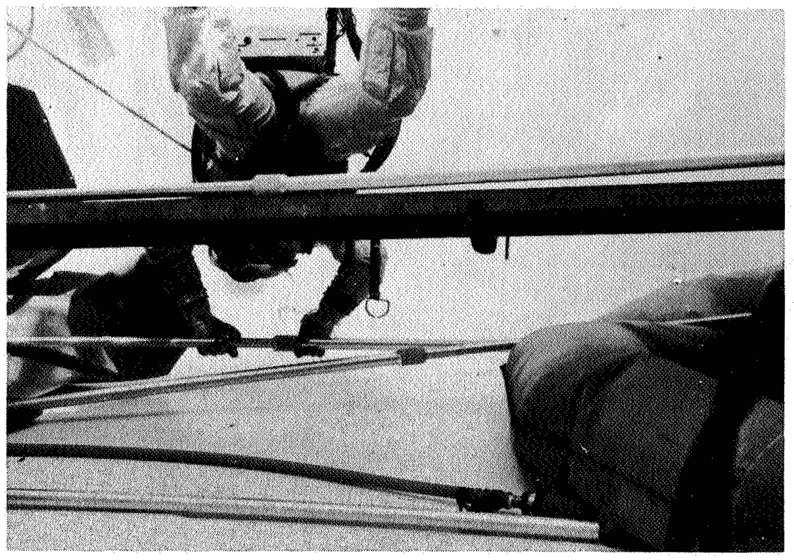
SUBJECT PRESSING WORK DOWN ON LADDER FOR CONTROL



SUBJECT ATTACHING INFLATING HOSE

F-7368

Figure B-26

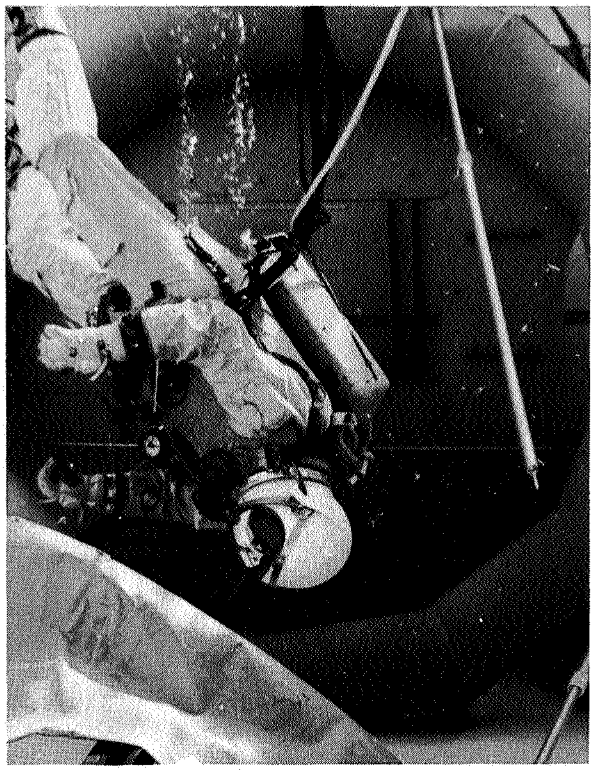


SUBJECT BEING CARRIEO TO BOTTOM BY WEIGHT OF ROD

F-7369

SUBJECT WITH LEGS THROUGH LADDER RUNGS, GOOD POSITION

Figure B-27

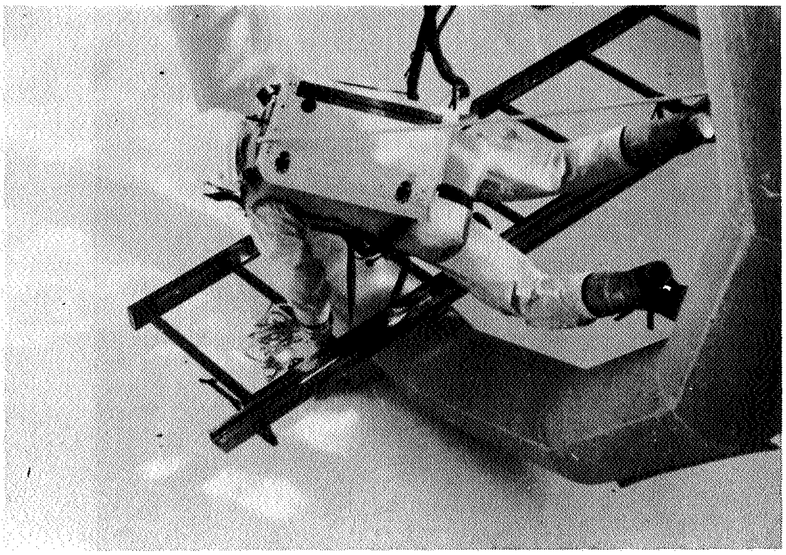


SUBJECT RESTING

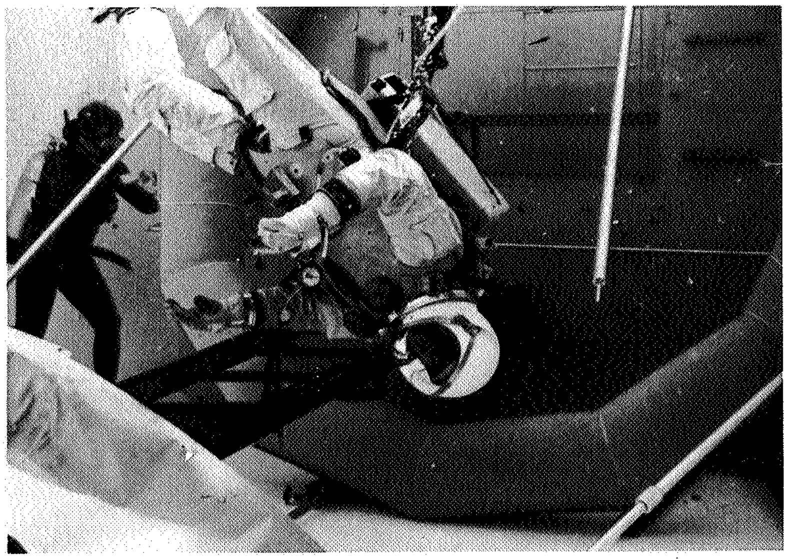
F-7370

SUBJECT POSITIVE IN BUOYANCY, FLOATING OUT OF CONTROL

Figure B-28



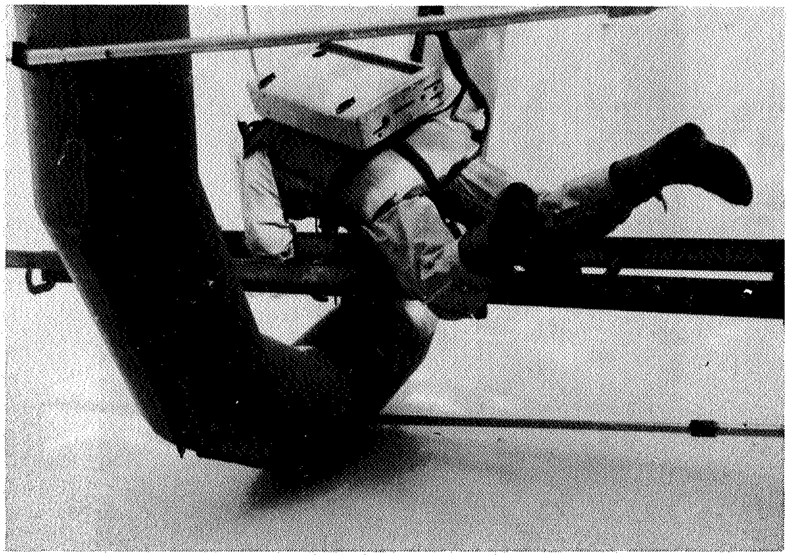
CONNECTING ROPE TO MOVE TWO INFLATABLE MODULES



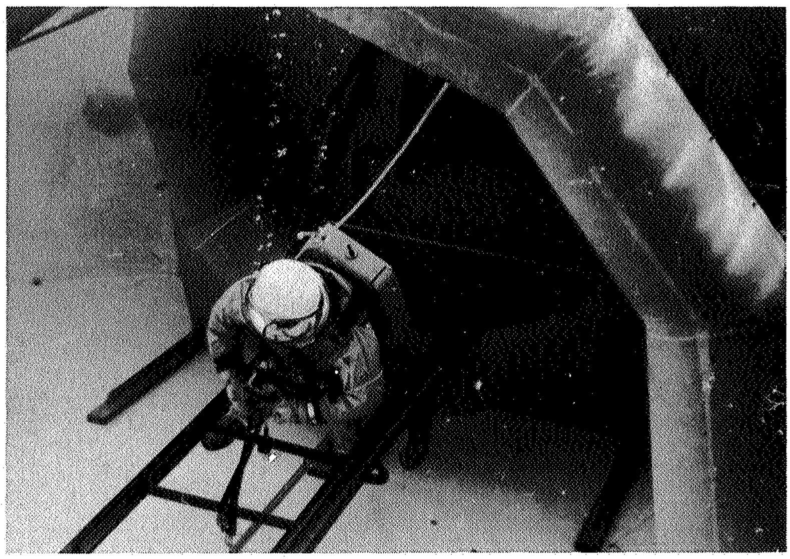
SUBJECT RESTING

F-7371

Figure B-29



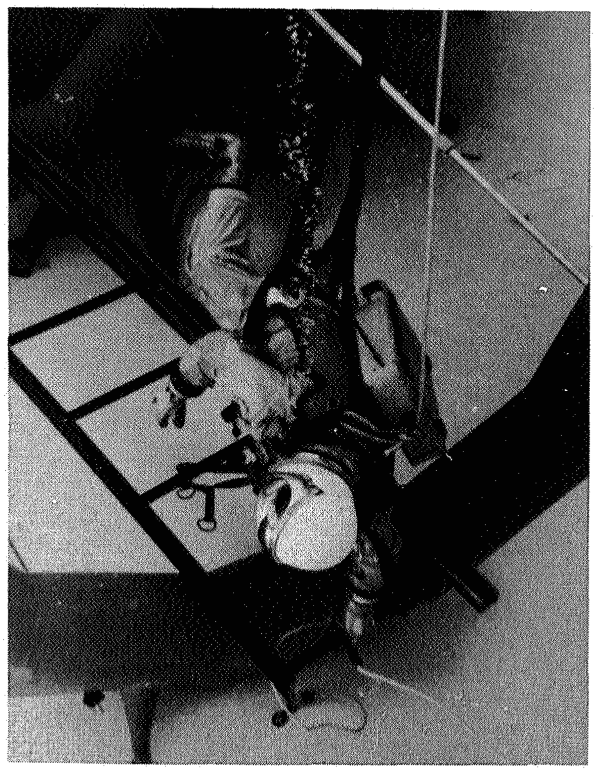
SUBJECT TRAVERSING FORWARD ON LADDER



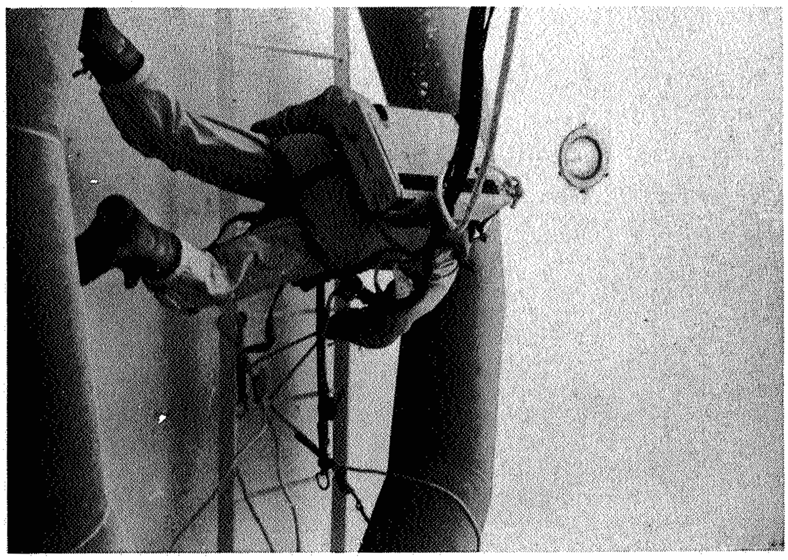
F-7372

SUBJECT SHORTENING STRAP RESTRAINT

Figure **B-30**



CONTROL AND POSITIONING DIFFICULTY IN CONNECTING ROPE

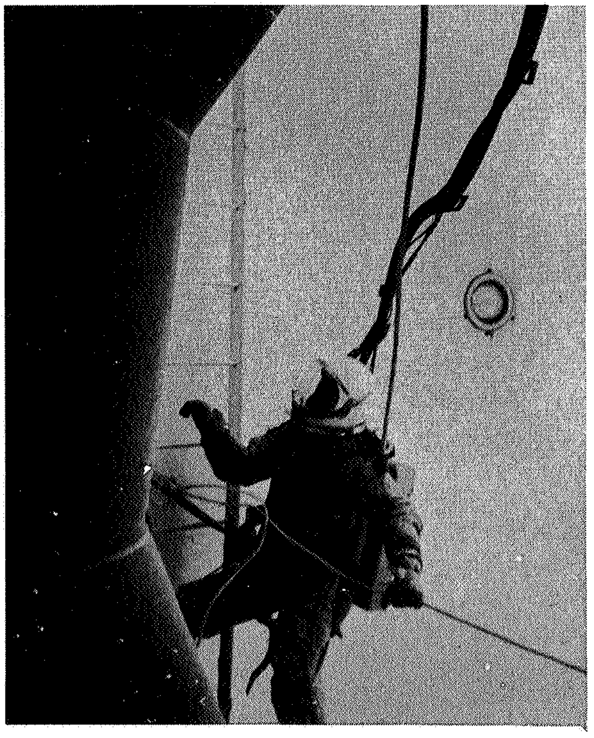


F-7373

TYING MODULE TO LADDER AFTER MOVING IT

Figure B-31

PULLING MODULE THROUGH WATER



F-7374

POSITIONING TO PULL MODULE (NOTE LEG BEHIND LAOOER)

Figure B-32

APPENDIX C

BIBLIOGRAPHY

PART I

1. Adams, C.R. and Hanaff, C., "Some Human Factors Considerations for Orbital Maintenance and Material Transfer." Aerospace Medicine Volume 36, March 1965, page 223-230.

Task Analysis used to determine 5 performance levels and to evaluate man's space-adaptive capabilities. Basic are shuttle design, space craft design, degree of automation involved, accessability, techniques for tasks performance, and recommendations are made.

2. Beasley, Greg P., "Investigation of a Simpl'ified Maneuvering Technique" and Thomas, David F. Jr., "Jet Shoe Extravehicular Activity Device" in National Conference on Space Maintenance and Extravehicular Activities, March 1966, page 311-31.12.

Reports on concept of a simplified integrated maneuvering system made up of low power thrusters and a tether to provide adequate extravehicular operations in space. Second part, present results of feasibility study into use of low-thrust jets mounted on soles of shoes. ..Motion could be controlled by instinctive movements of feet and legs.

3. Beckman, E.L., K.R. Coburn, et al "Some Physiological Changes Observed In Human Subjects During Zero G Simulation By Immersion in Water Up to Neck Level." Naval Air Development Center, Johnsville, Pa. Rept. NO. NADC MA 6107. AD 256 727, 1961.

Knowledge relative to the effects of prolonged weightlessness is needed in preparing man for space flight. The buoyant force exerted upon imnersed bodies effectively simulates the weightless state with respect to proprioceptive sensory responses and perhaps in other ways. An investigation into the physiological effects of immersing subjects in water up to neck level was undertaken. A series of experiments involving 7 subjects immersed in water up to neck level for periods of 5 to 23 hours (5 subjects for 12 hours) showed a significant weight loss during the period of imnersion, which was explained by the diuresis which occurred. Pulmonary volume measurements showed a decrease in the expiratory reserve volume and in the respiratory minute volume during immersion. There was no significant decrement in the performance of a tracking task, attributable to the water immersion, during exposure to a simulated space vehicle reentry deceleration profile. Exposure to 4.5 positive G for 15 seconds following water immersion revealed a decrement in tolerance in most subjects.

4. Benson, V.G., E.L. Beckman, et al 'Weightlessness Simulation By Total Body Immersion. Physiological Effects." Naval Air Development Center, Johnsville, Pa. Report No. NADC-MA-6134. AD-263 194, 1961.

Attempts have been made to simulate the weightless state by immersing subjects in water up to the neck level for varying periods of time. These subjects were exposed to acceleration forces on human centrifuges before and after immersion. A reduction to the ability to withstand these acceleration forces was noted following the immersion period. Immersion in water to the neck level produces a negative pressure breathing situation which in turn results in a profuse diuresis. An attempt was made to eliminate the negative pressure breathing and the diuresis by equipping the subject with a full face diving mask with a compensating regulator and completely immersing him in water for a period of twelve hours. Of the seven subjects tested, only three were able to tolerate the 12-hour period of water immersion. The remaining four terminated early in the study due to the stress of the underwater environment and were not exposed to acceleration forces following their immersion periods.

5. Bourne, Geoffrey H. (Emory University, Dept. of Anatomy, Atlanta, Georgia.), "Neutromuscular Aspects of Space Travel." in Physiology of Man in Space. New York, Academic Press, Inc., 1963, page 1-59.

Discussion of the muscular stresses in space flight resulting from weightlessness and high-g conditions. Radiation effects are also briefly noted. The macroscopic and microscopic structures of muscles and their methods of action and innervation are studied. The responses of sense organs to subgravity are tabulated. Illustrated are short-term water- immersion tanks, related equipment, and other zero-gravity simulators.

6. Brown, J.L., "Orientation to the Vertical During Water Immersion," J. Aerospace Medicine, 32:209-217, March 1961.

Subjects were immersed in water at a depth of either 18 or 25 feet and then rotated in a tucked position on a rod through 3, 4, or 5 revolutions. Rotation was terminated with the head in one of 4 positions: upright, inclined forward, down, or back. Upon termination of rotation subjects were directed to point in the up direction, then to nod the head and correct in the direction of pointing if necessary, and finally to swim toward the surface. There were errors in direction of initial pointing of as much as 180 degrees. Errors were greatest with the head down or back and least with the head up or forward. Nodding of the head was followed by consistent improvement in the direction of pointing. There was little indication of any difficulty in swimming in the upward direction. Greater density of the legs as compared to the trunk resulted in fairly rapid vertical orientation of the body upon release of the rod. The results are interpreted to reflect the relative inefficiency of the utricles as gravity sensors when the head is in certain positions. The simulation of zero gravity may be enhanced by utilizing these positions with water immersion.

7. Buckout, K., "A Working Bibliography on the Effects of Motion on Human Performance," July 1962, 56 page 546 Refs. MRL-TDR-62-77 Issue 19.

Abstract: A number of disciplines which bear on the problem of motion and its effect on human performance. Included are studies of tumbling and weightlessness. Finally reports on training and motion simulation, equipment and methodology and general analysis of the whole problem area are presented.

8. Caidwell, L.S., "Body Position and the Strength and Endurance of Manual Pull," Human Factors, volume 6, October 1964, page 479-484.

Strength and duration for sub-maximal holding response for 20 body positions. Experimenters concluded that a change in body position, which increases strength will reduce effort to maintain a given force and the endurance of the holding response will increase.

9. Campbell, P.A. and S. J. Gerathewohl "The Present Status of the Problems of Weightlessness." Texas State Journal of Medicine 55(4):267-274, April 1959.

Reports weightless orientation studies made by immersing men in water. Man's ability to orient himself depends upon a variety of factors, and during weightless situations the eye becomes the only reliable organ.

10. Corrado, R.P., "A Study of Retrieval Techniques for Tethered Astronauts." System Engineering Group, Research and Technology Division Air Force System Command, Wright-Patterson AFB, Ohio, July 1965.

Abstract: Math models used to investigate three methods of retieval, the constant, anchor-mass, constant tension technique, line wrap, space craft rotation, excessive terminal velocities etc., made modes unacceptable for long retrieval distances.

11. Costick, John F. 111, "The Necessity for Development and Use of Fastening Devices with Special Characteristics for Space Use." National-Conference on Space Maintenance & Extravehicular Activities. March 1966, page 271-278.

Summary: Tool fastener interface problems relative to extra-vehicular space with particular interest to the problem of push-off. (Simulators have shown that 2 pound force applied for 0.1 seconds will cause an astronaut to drift out of reach of the space craft in 30 seconds). Fasteners for no end leading are examined to alleviate the push-off problem,

12. David, H.M., "Weightlessness Lowers Performance," Missiles & Rockets 8(21): 36 May 22, 1961.

Physiological and psychological studiesconducted under conditions of weightlessness have brought to light situations which may pose a serious problem to space flight.

13. Dempster, W.T., "The Anthropometry of Body Action," Aerospace Medicine Lab, Wright-Patterson AFB, Dayton, Ohio, WADD Tech. Rept. 60-18, ASTIA AD-234005, January 1960.

Abstract: If a dynamic anthropometry relating to body movements is to be deieloped it must proceed on body kinematics and the forces in relation to posture and movement. The actual movements must be studied and recorded.

14. Diringshofen von, H. "Immersion in Water as a Partial Simulator of Weightlessness in Space Medicine." Archiv für Physikalische Therapie (Leipzig), 14(4): 307-311, July-August 1962. (Germany)

Research on weightlessness employing water-tank simulators is reviewed in the light of Titov's experience in space flight. Certain disturbances in the physiological functions seen in the experiments were caused by the hydrostatic pressure of the water. A progressive muscular asthenia with increasing tendency to orthostatic collapse developed in the experimental subjects as a direct effect of the hypodynamic environment. This tendency still persisted two days after the seven-day experiment in the water-tank simulator. The lowered stress resistance was evidenced by lowered acceleration tolerance, lowered physical efficiency in the presence of unimpaired muscle strenth, and in particular by lowered sensorimotor performance. The electro-encephalogram showed a disturbance in the sleep-awakefulness cycle, i.e., frequent intervals of light sleep or lowered consciousness and only two hours of deep sleep. Recommendations include a program of systematic physical exercise aboard the space ship to maintain muscle and cardiovascular tonus, and training of spatial orientation to compensate for the non-function of the otoliths in zero-gravity conditions.

15. Dunn, J.P. & Skidmore, R.A., "An Analytical Procedure for the Design and Evaluation of Crew Work Stations." In American Institute of Aeronautics and Astronautics and NASA Manned Space Flight Meeting, 3rd, Houston, Texas. November 4-6, 1964, Technical Papers (AIAA Publication CP-10) New York, American Institute of Aeronautics & Astronautics 1964, page 153-165.

A sequential analysis is performed which contains system definition task analysis, Preliminary Display & Control layout, time and duty analysis and mathematical verification which yields a graphic time line analysis showing new size, duties, interactions, malfunction and abort sequences, percent utilization of each crew member and actual operating times. These outputs are shown in relation to time and such eniironmental factors as g load and vibration. Times are derived from a mathematical model whereby all functional operations, instrument interpretations, control movements, and error compensating factors are combined in a single equation that provides real-time answers.

16. DuBois, J., Santschi, W.R., Watson, D.M., Scott, C.O., and Mazy, F.W., "Moments of Inertial and Center of Gravity of the Living Human Body Encumbered by a Full Pressure Suit." AMRL-TR-64-110, Aerospace Medicine Research Lab, Wright-Patterson AFB, Ohio, November *1964.*

Abstract: The center of gravity and the moment of inertial of each of 19 male subjects. Two positions used, sitting and relaxed and three modes of dress, (1) nude, (2) suited and unpressurized, and (3) suited and pressurized. Theoretical accuracy of the experiment, based on a compound pendulum, ranged from 2 to 8 percent depending on body position and axis the moments of inertia were found to vary significantly between body positions and between nude and suited conditions. Correlation coefficients between the moment of inertial and stature and weight exceeding 0.9. Fifty anthropometric dimensions and frontal and profile photos were obtained on each subject to serve as the basis for additional biodynamic analysis.

17. Dzendolet, E., & Rievley, J.F., "Man's Ability to Apply Certain Torques While Weightless." WADC Technical Report 59-94. Wright-Air Dev. Center, Wright-Patterson AFB. Ohio.

Abstract: The torque that a maintenance man can exert within a space vehicle while weightless and hence, tractionless, is analyzed. Anthropological literature was reviewed to determine the torques a man can apply under normal conditions. Using elementary physical principles the consequences of applying these torques while tractionless were calculated. Certain of the the predictions were verified experimentally. It is tentatively concluded what standard anthropometric data can be legitimately extrapolated to the weightless condition.

Suggestions are advanced regarding (a) the optimum body position for the simple tightening task without using handholds, (b) the use and location of handhoids, (c) the maximum torque limitations, (d) the use of impulse, and (e) the design of hand tools.

18. Dzendolet, E., "Manual Application of Impulses While Tractionless." WADD Technical Report 60-129. Aerospace Medical Lab, Wright-Patterson AFB Ohio, February 1960.

Abstract: The percentage of naive subjects who, while tractionless in a horizontal plane anchored by one handhold, push in or pull out a plunger in one motion against various frictional forces and travel distanced, decreases directly as a function of the force and distance required. With large-force impulse, the impulse is linear and the situation can be described by the impulse momentum theorem $f_0{}^J Fdj = MV_1 - MV_0$. The shape of the impulse is saw-toothed and its area approximated by taking three-fourths of the area of a rectangle whose base is the duration and height, the force of the impulse. For this experiment, the maximum duration of an effective impulse for a sequence force of 40 lbs. is 0.5 seconds for a push-in and 0.3 seconds for a pull-out impulse, etc.

19. Elkins, Wm., "Hard Shell Suit Performance As It Relates To Space Maintenance and Other Extravehicular Activities." in National Conference on Space Maintenance Extravehicular Activities, March 1966, page 511-516.

Sumnary: Sales pitch for Litton hard suit, but informative. Chart showing weight saving in expendable over a 30 day period of use to 156 lbs of material - claim reduction of metabólic requirement by an order of magnitude over soft suits.

20. Ferguson, John C. and Randall M. Chambers "Psychological Aspects of Water" Immersion Studies Report No. 7. Naval Air Development Center, Johnsville, Pa., Aviation Medical Acceleration Lab. 30 Dec 1963, 28p. (NADC-MA-6328; AD-429523). N64-15755.

The purpose of this paper was to review the recent water immersion literature, placing special emphasis on the psychological aspects of these studies. Theadequacyof water immersion as a technique for simulating weightlessness was discussed, and water immersion facilities and procedures were described. The areas of perceptual and motor performance, boredom and fatigue, sleep, orientation, and personality and emotional aspects of water immersion were selected as being of special psychological interest.

21. Gerathewohl, S. J., "Zero-G Devices and Weightlessness" Simulators. National Academy of Sciences, National Research Council, Washington, D.C. Publication No. 781, 1961.

This report concerns the devices, methods, and techniques which have been used for the investigation of the effects of zero-G and weightlessness by many investigators. The report is not a scientific treatise of the problem of weightlessness and the effect of sub- and zero gravity upon the organism,but rather a description of research equipment techniques.

Concerns the devices, methods, and techniques, which have been used for the investigation of the effects of zero-G and weightlessness by many investigators. Part I deals with devices which can be used for producing sub- and zero-gravity, viz., vertical-motion devices, aircraft, and ballistic missiles. A simple mathematical treatment of the physical parameters involved in sub- and zero-G conditions precedes the discussion of each of these three methods. In Part II, instruments and techniques for the simulation of weightlessness are described, The objective of this survey is to assure maximum usefulness of such devices and optimum cooperation between agencies and to guaranteethat new requirements of the future be incorporated in research proposals on bioastronautics.

22. Serathewohl, S. J., "Effects of Weightlessness on Man Durinq U.S. Sui -Orbital and Orbital Flights." NASA Ames Research Center N65 29487, 1963.

The astronauts responses to weightlessness during the project Mercury flights are analyzed. Physiological parameters are discussed.

23. Goodman, J. R., and Radonfsky, M. I., "Lunar Surface and Free Space Hazards Relating to Space Suit Design," Journai of Environmental Sciences, volume 8, June 1965, page 26-31.

Discussion of anticipated lunar environment including atmosphere terrain, gravity test, EMU described, some of the testing aids used to simulate the lunar environment are considered.

24. Glazer, D.L., and Trhill, B.A. Jr., "Operator/Tool Interface Problems Areas for Space Maintenance," in National Conference on Space Maintenance and Extravehicular Activity. March 1966, page 561-5.6.10.

Summary: Operator performance and hand tool evaluation study, using suits and shirt sleeve, at 1/6 G. Test panel of standard components used with standard tools, results and recommendations made. Good Study.

25. Hammer, Lois R., "Aeronautical Systems Division Studies in Weightlessness:" 1959-1960. Aerospace Medical Laboratory, Aeronautical Systems Division, W-P Air Force Base, Ohio. December 1961. (Proj. 7184; Task 71595). WADD TR 60-715. AD 273098.

Facilities and techniques used at Aeronautical Systems Division to study the effects of weightlessness are described; completed experiments and those started before January 1961 are discussed. Topics are grouped under two main headings: aerospace medical studies and aeromechanics studies. Specific problem areas and methods of experimentation are emphasized. Findings are briefly stated.

The Biomedical Laboratory Water Submersion Task is discussed in Section 11, Facilities and Methodology. Studies of the Psychophysiology Effects of Prolonged Weightlessness employing the water submersion tank are discussed in Section 111, Aerospace Medical Studies.

26. Hanavan, E.P., "A Mathematical Model of the Human Body." Aerospace Medical Research Lab, Wright-Patterson AFB, Ohio. August 1964. AMRL-TR-64-102.

Abstract: Mathematical model for predicting the inertial properties of a human body in various positions, 25 std anthropometric dimensions are used in the model to predict an individual's center of gravity, moments and products of inertia, principal axes, a generalized computer program to calculate the inertial properties of a subject in any body position is presented.

27. Hartman, B., McKenzie, R. E., and Graveline, D. E., "An Exploratory Study of Changes in Proficiency in a Hypodynamic Environment." School of Aviation Medicine, Brooks Air Force Base, Texas, Report No. 60-72, July 1960. AD 244 121.

Simulated weightlessness for a prolonged period was produced by the body immersion technique. Changes in psychomotor efficiency was assessed during immersion and after return to the normal environment of 1 G. Systematic changes in a relatively simple task were obtained during immersion. Gross disruptions in psychomotor behavior on return to the normal environment were observed. Accompanying this were increased response times on three different kinds of tasks in a systems operator simulator. These results suggest that the functional capabilities of a man, while adequate during prolonged weightlessness, will be seriously impaired during the reentry phase of space flight.

28. Hertzberg, H.T.E., "Dynamic Anthropametry of Working Positions." Behavioral Science Lab Aerospace Medical Division, Wright-Patterson AFB, Ohio Project 7222; ASDTR 61-90: ASTIA AD-263-715. (See also Reprints Human Factors page 147-155, August 1960.

Abstract: The proper method of workspace design, the design limit concept is described, methods for gathering data on body size, strength data are outlined and major information sources noted.

29. Hertzberg, G. T. E., Dupertuis, C.W., and Emanuel, I., "Stereophotogrammetry as an Anthropometric Tool." Wright Development Center, Wright-Patterson AFB,Ohio,WADC Technical Report 68-67, ASTIA AD-150964 February 1958.

Paper outlines with illustrations the procedure used to draw human body contours a 1/2 inch intervals, it discussed the utility of stereo data for anthropometric purposes, and further applications and considered.

30. Hess, W.H., and Konecci, E.B., "Approach to Reduced Gravity Studies for Human Experimentation" Douglas Aircraft Company, Inc., Santa Monica California, engineering paper: No. 1189 Sept. 14, 1961, also Aerospace Medical 33 (11): 1397-1398 November 1962.

Subjects attached to three helium filled balloons. Test conducted (a) target by blind positioning, (b) pulling against reduced traction, (c) pushing against reduced traction,(d) applying torque against reduced traction.

31. Hewes, D.E., and Spady, A.A. Jr., "Evaluation of a Gravity-Simulation Technique for Studies of Man's Self-Locomotion in Lunar Environment." NASA Tech-Note D-2176

Summary: Consideration of need for new and different types of gravity-simulation techniques. Inclined plane type developed and tested. Coverage of tests, walking, jumping, stairs, ladders, and poles. Film of tests available on request.

32. **Hirsch,** A.E., and White, L.A., "Mechanical Stiffness of Man's Lower Limbs," David Taylor Model Basin, Washington, D.C., Structural Mechanics Lab.

Measurement of compressibility of mechanical stiffness of limbs under static loads. Major load being regions of foot are intensified.

33. Holmes, A.E., "Design, Fabrication, and Installation of Six-Degree-of- Freedom Space Maintenance Simulator, Technical Report AFAPL-TR-64-129, Air Force Propulsion Laboratory, Research and Technological Division, Air Force System Communications. Wright-Patterson AFB, Ohio, April 1965.

Abstract: The simulator supports a 180 lb. and a 110 lb. back-pack with unlimited freedom in pitch, roll, and yaw; horizontal translation on frictionless air pads over a 20 x 20 ft. floor; and vertical translations on air beaming ±18 inches from nominal position. Also included was a servo controlled work panel. Capable of horizontal translation simulating a 3K to 7K lb object in orbit. The work panel is suspended from a 20 foot span bridge crane with both axes controlled by servo amplifiers housed in a single rack. A 140 SCF air tank provides a low rate air spring for central translation.

34. Holmes, A. E., and Hamelton, A. L. , "A Space Tool Development Program." in National Conference on Space Maintenance & Extra-Vehicular Activities, March 1966, page 2.1.1 - 2.1.15.

Summary: Martin Company & Black & Decker built power tool and three zero reaction attachments, to be used for repair assembly in orbit and on moon. Study (supposedly) based on iniestigation of expected maintenance tasks and H.F. considerations. Tool works with saw, impact wrench and drill attachments. Restraint capability required for some functioning and is provided by adhesive.

35. Kama, W.N., "Speed and Accuracy of Positioning Weightless Objects as a Function of Mass, Distance, and Direction." WADD-TR-61-182, March 1961, Wright-Patterson AFB, Ohio.

Human Performance in positioning weightless objects was investigated by using air-bearings end frictionless table. Subjects moved four masses 1000, 3000, 5000, & 7000 grams, various distances - 10, 20, and 40 cm. Investigators concluded that mass had little effect on accuracy of positioning, distance is a significant variable affecting error. Direction of movement is a significant iariable affecting constant error.

36. Kasten, D. F., "Interdisciplinary Measurement of Human Performance Under Low and Zero Gravity Conditions," in AFSC 11th Annual Air Force Science and Engineering Symposium (1964) 13 p, Aerospace Medical Division Aerospace Medical Research Labs, Wright-Patterson AFB, Ohio.

Interdisciplinary Studies of human locomotion under conditions of weightlessness.

37. Kasten, D.F., "Analysis of Human Motions in Orbital Space" (paper, 33rd Annual Meeting of Aerospace Medical Association, Chalfonte-Hadden Hall, Atlantic City, N.J., April 9-12, 1962)

Qualitative review of some seldom considered H.F. problems which may confront weightless workers in a space environment. Discussion is based on inflight zero G research, computer simulation studies. Topics include, human locomotion and rotation in weightlessness, frictionless environment, problems in tethering.

38. Kitayev-Smyk, A., "Man in a State of Weightlessness" (a translation) Foreign Technology Division, AFSC, Wright-Patterson AFB, Ohio, September 27, 1965.

Summary of experiments and subjective observations in Russian parabolic trajectory flights. includes what people feel in state of weightlessness and physiological explanation. Experiments on vision, hand-eye coordination.

39. Kulwicki, P.V., Vergamini, P.L. and Schlei, E.J., "Weightlessness-Self-Rotation Techniques." Wright-Patterson AFB, Ohio." Behavioral Science Lab, October 1962. AMRL-TR-62-129.

The concept of self-rotation is analized by the application of theoretical mechanics to a rigid mathematical model composed of six cylindrical segments. Nine maneuvers are selected to provide an effective solution.

40. Lawton, R.W., "The Pathophysiology of Disuse and the Problem of Prolonged Weightlessness: A Review." Report for December 1960 - March 1963. June 1963, 46p. General Electric Co., Philadelphia, Pa. (Proj. 7222, Task 722201). AMRL TDR63-3. AD-417 395.

The physiological implications of zero-G as encountered in space flight are discussed and the available research concerning the physiological effects of weightlessness is reviewed. The purpose of this review is to proceed from the present state of knowledge of normal human physiological systems, particularly as their structure and function are affected by gravity, to a consideration of the possible physiological consequences of prolonged human exposure to zero-G are briefly reviewed. The data suggesting that prolonged weightlessness will be a deconditioning environment is presented. These data are considered for possible outward effects of prolonged exposure to weightlessness, and for methods of prevention of undesired effects. The problem of artificial gravity by rotation of a space vehicle is briefly considered. Areas of needed future investigation are suggested.

41. Lee, Wm. L. Jr., "Problems in Person Protection and Performance During Extravehicular Operations," in A. F. Academy Product of 1st Annual Rocky Mountain Symposium (1964) page 123-140.

Coverage of the problems of protecting man in space without interfering with his performance capability, eg., EVA.

42. Levine, Raphael B., "A Device for Simulating Weightlessness." Lockheed-Georgia Company, Marietta, Georgia, in Medical and Biological Problems of Space Flight, page 85-113. Proceedings of a Conference held in Nassau, the Bahamas, November 1961, Academic Press, Inc., 1963.

Design and instrumentation for a successful weightlessness simulator are discussed in terms of the three major effects it must produce: (1) deprive the subject of all important sensor cues (visual, mechanical, balance) to the existence of a gravitional field; (2) produce as many as possible of the important physical and physiological effects (on vestibular function, respiration, diurnal rhythms, locomotion, manipulation skill, muscle, bone, and cardiovascular function, cause motion sickness) of a true gravity free state; and (3) appeal psychologically (exhilaration, isolation, physical contact loss) to the subject as a true representation of acutal space flight conditions in as many modes as possible. The Lockheed null-gravity simulator gives promise of fulfilling these conditions. It consists of a large tank filled with water in which the subject is immersed; the tank and its contents are rotated rapidly at a constant speed. Basic experimental procedures in using the simulator (subject fitting, positioning system, breathing air system), and safety measures are discussed.

43. Loats, Harry L. Jr., Mattingly, Samual G., and Bruch, C. E., "A Study of the Performance of an Astronaut During Ingress and Egress Maneuvers through Airlocks and Passageways." 4 Volumes, April 30, 1965. NASA contract 1-4059 Performed by Environmental Research Associates, P.O. Box 454 Randallstown, Maryland.

Summary: Water Immersion correlated with zero-G aircraft flights. Airlock 48" x 72". Aircraft flights allowed only 5 to 10 percent of time necessary to perform task. Procedures of study presented to great detail.

44. Loftus, J. P. and L. R. Hammer, "Weightlessness and Performance: A Review of The Literature," Aerospace Medical Laboratory, Wright-Patterson Air Force Base, Ohio, June 1961, ASD-TR-61-166.

The implications of weightlessness as encountered in space flight are discussed, and the known research dealing with the psychological and physiological effects of zero gravity is critically reviewed. Topics are grouped under the headings of orientation, psychomotor performance, and physiological functions, with a special section on methods of research. The major problem area indicated is the effect

a

of weightlessness on gravity oriented sensory mechanisms, particularly the vestibular apparatus, and consequently on both physiological functions and psychomotor performance, An extensive bibliography is included.

Immersion techniques are discussed in the section devoted to Methods of Research, page 5-6, and a review of immersion studies reported in the literature published prior to April 1961 is presented in the section devoted to Physiological Functions, page 21-22.

45. Margaria, R, and Cavaga, G.A., (of Milan University, Italy) "Human Locomotion of Subgravity," Aerospace Medicine, Volume 35, Dec 1964, page 1140-1146.

Summary: Simulating sub-gravity on earth is discussed. In walking at one-g kenetic potential energy level are in phase opposition, forward acceleration is obtained through transformation of potential into kinetic energy, walking on the moon would be almost impossible. Because of the lower weight of the subject, the vertical component of the force may be too low to maintain the adherence of the foot on the ground and prevent skidding.

46. Marton, T., Hunt, R., Klaus, T., Cording, C.R., "Neutral Buoyancy Submersion for the Analysis of Human Performance in Zero 'G'," Valley Forge Space Technology Center, General Electric Co., Philadelphia, Pa. Presented at AIAA meeting October 11-13, 1965, St. Louis, Missouri.

Study conducted with scuba gear, console display and control reaction time compared to one-g base line, all submersion test took longer, some by 50 percent. No significant advantage found between three types of restraints used, i.e., handhold, toe hold, and thigh straps; but empiricalevaluation points to the advantages of toe and thigh restraints. Gross high speed movements in submersion require as much as 30 percent more task time.

47. May, Chester B., "Maintenance in a Weightless Environment," ~~Air~~ Force Aerospace Propulsion Lab., Wright-Patterson Air Force Base,

Summary: Discussion of zero simulation for maintenance equipment and in space maintenance experiments. Zero 'G' aircraft flights and a six-degrees-of-freedom suspension simulator are compared and shortcomings of each are noted. All simulated tasks need actual space flight data for verification.

48. May, Chester B., Schofield, Capt. J.N., and Vorst, L.A. , "AF-Gemini Space Maintenance Experiment Simulation," in National Conference on Space Maintenance and Extra-Vehicular Activities March 1966, page 4.1.1-4.1.18.

Summary: Design and simulation study of the Air Force D-16 in Space Maintenance Experiment. Section 1 defines orbital space experiment, parameters, instrumentation and data analysis. Section

2 discusses a cross validation study in terms of experimental design, instrumentation and data analysis.

49. Meineri, G., "The Effects of Subgravity and the Methods for Reproducing it on the Ground and in Flight." Rivista di medicina aeronautica e spaziale (Roma), 26 (1): 80-98. Jan-Mar 1963. (in Italian, English Summary (page 94)).

A review of the literature is presented which deals with experiments on the physiological effects of subgravity. The chief methods used to simulate subgravity conditions are described and a distinction is made between ground methods (immersion of all or part of the body in water, high acceleration exposure), and the more cumbersome methods through which actual or complete subgravity can be attained (parabolic flight, suborbital and orbital launching). The accomplishments are reported of the Center of Studies and Researches in Aerospace Medicine, Rome, which uses a subgravity tower for experiments. This tower is of great value in obtaining data on the physiological effects of short-term subgravity similar to that encountered in space flight, such as transition between the active and passive stage of flight, the effects on psychomotor behavior, the role played by the labyrinth and its components, etc. The possible extension of these methods into worldwide space research projects is discussed.

50. Mercer, J., "S-IVB Stage May Become Space Station," Missiles and Rockets, April 25, 1966, Volume 18 #17, page 17.

Study on feasibility of using Saturn upperstage 20 foot long 21.7' diameter as space station. Airlock would be fitted and hydrogen tank pressurized to 5 psi, 100 percent O_2 ... 30 day experiment, interior and exterior.

51. Miller, A.K., and Lincoln, R.S., "Study of Human Performance in A Mark IV Pressure Suit." N65-31557. Lockheed Missile and Space Co., Sunnyvale, California, 15 November 1964 (LMSE-6-62-64-19).

Two subjects wearing pressurized and unpressurized Mark IV suits. The study was to provide an evaluation of performance tasks, i.e., tracking-push buttons, etc. Degradation due to suits noted, turning of wrists and internal pressure disadvantages.

52. Morway, Donald A., Richard G. Lathrop, et al "The Effects of Prolonged Water Immersion of the Ability of Human Subjects to Make Position and Force Estimations." Aviation Medical Acceleration, Lab., Naval Air Development Center, Johnsville, Pa. 24 July 1963, 21 p. NADC MA6115;5. AD-414 349.

Twelve subjects using underwater breathing apparatus were imnersed in water for 18 hours. Each subject's responses to two general psychomotor tasks: (1) the ability to reach and position the arm and hand accurately and (2) the ability to estimate a prelearned level of force, were measured before, during and after water imnersion. Analysis of variance performed upon the target aiming task showed no significant difference in the horizontal aiming component. However, a highly significant (p less than .01) bias upwards was observed in the vertical aiming component. Comparisons between trial means using the Duncan q' test indicates that the bias upwards declined as a function of imnersion time. An analysis of variance performed upon the force estimation data showed a significant interaction between trials within blocks and test conditions. Duncan's q' Test Ordered Means Comparison revealed no significant difference between the pre- and post- imnersion force estimations. The mean estimation obtained during imnersion was significantly different (p less than .01) from the pre- and post-trials. The force data showed no tendency to adapt as a function of time immersed.

53. Mueller, D.D., and Simons, J.E., 'Weightless Man: Single Impulse Trajectories for Orbital Workers." Technical Document Report No. AMRL-TDR-62-103 September 1962. Aerospace Medical Research Labs., Wright-Patterson AFB, Ohio.

Summary: In space a worker may propel himself away from the vehicle, to determine the speed of such a single-impulse launch it was simulated in a zero G KC 135 aircraft, S's attained speeds of approximately 10 mph, motion results in a trajectory such that worker would never return to his vehicle.

54. "NASA - Engineering Research Experiments for Manned Earth Orbital Missions." Performed by Federal Systems Division of IBM Corp., Rockville, Maryland, NASA Contract NAS1-4667, July 1965.

Summary: Final oral presentation charts, study develops the rationale, structure, and methodology of implementation of a comprehensive engineering experimental program to support and advance the intrinsic technological goals or the National Space Program. Tests and procedures are covered with hardware concepts.

55. "NASA - Experiment Descriptions for Extended Apollo Earth-Orbit Flights," National Aeronautics and Space Administration, WASHQC, March 15, 1965, Preliminary Data, Part I, Section 1-4 only, (For Officials Use Only) .

21 medical experiments, e.g., head rotation in weightless, exercise (work) capacity and circulatory, evaluation of muscle mass and strength.

3 behavior experiments, e.g., psychomotor functions.

2 creation of artificial gravity, e.g., rotating space station and onboard centrifuge.

56. "Needed: A Theory of Weightlessness," in its Soviet Research in Bioastronautic 10 March, 1965, page 15-19.

Consideration is given to various aspects of weightlessness. With emphasis on its effect on man in this condition for extended periods of time, other areas of study included accuracy of movement and energy expenditure.

57. Parker, F.W., and Garnett, "The Astronaut Maneuvering Unit," in National Conference on Space Maintenance and Extra-Vehicular Activities, March, 1966, page 3.2.1-3.2.18.

Summary: The A.M.U. Backpack maneuvering unit provides life support, propulsion, communication and automatic altitude stabilization and permits the astronaut to operate as an independent small maneuverable spacecraft system. Paper presents results of study conducted to develop and evaluate an AMU used to support space station experiments and operational activities. AMU experiments were defined and missions established to determine performance requirements. EVA operations summarized, antenna erection shown.

58. Peters, George A., and Hall, Frank S., Rocketdyne, Canoga Park, Calif. "Source Document for Human Factors Engineering," including associated areas in Subsystem Safety, Maintainability, Personnel Subsystems, Life Sciences, Quality Assurance, and Reliability Engineering. 1 January 1965, 168 pages.

380 Report Sources listed - 371 are regulatory and guidance documents, reviews state-of-the-art and contractually required data submitted reports, and how it was done and type of organization used.

59. Peters, G.H., Shafer, R.J., and Hanny, J.F., "Extra-Vehicular Capsular Adhesive Systems." in National Conference on Space Maintenance and Extra-Vehicular Activities, March, 1966, page 2.2.1-2. . .

Summary: Positive attachment for space maintenance. Attachment device consists of a belt or harness to which are fastened three telescoping legs, Legs are tipped with adhesive pads, or dispenser filled with pads, which will adhere to any work site upon activation. Astronaut would "glue" himself to side of space craft and have six degrees of stabilization while retaining the use of his arms and legs.

60. Pierce, B.F. and E.L. Casco, "Crew Transfer in Zero G as Simulated by Water" Immersion. General Dynamics/Astronautics, San Diego California, 15 April 1964, GDA-ERR-AN-502.

The essential characteristic of man that makes water immersion a feasible method of weightless simulation for analyzing the relationship of man to equipment is that the specific gravity of the human body is equal to about one. Having approximately neutral buoyancy, the subjects representing the crew can assume positions and movements relative to the

mockup which are similar to those that would occur in weightlessness, but which would be unattainable under one-g conditions.

The major limitation of this technique results from the fact that water offers considerable resistance to movement, and the resultant restriction to body mobility (as well as well as the possibility of using this resistance for self-propulsion) must be taken into consideration. Nevertheless, water immersion provides the best simulation of weightlessness for periods of unlimited duration and with equipment of unlimited size.

61. Pierson, W.R. and Geller, R.E., "Work in a Low Friction Environment," Life Sciences Lockheed, California Company, Burbank, Calif. Paper presented in AIAA 4th Manned Space Flight Meeting, October 11-13, 1965, St. Louis, Missouri.

Summary: 18 subjects tested in six-degrees-of-freedom simulator, pressurized to 3.5 psid, performing 3 maintenance tasks, grip force same in time and effort as one-g, tasks requiring reactions require more time, body restraints required for torquing forces, hand-eye coordination not affected, much of decrement due to pressure suit, and suit improvements are recommended.

62. Pigg, L.D., "Human Engineering Principles of Design for In-Space Maintenance." Behavioral Science Lab., Wright-Patterson AFB, Ohio ASD-TR-61-629 ASTIA AD-271, 066, Nov 1961.

Abstract: Results of research on problems related to human performance of maintenance actions in space systems are reviewed. The interaction of sensory, psychomotor, and motor functions are discussed, along with problems of remote handling in space.

63. Samuels, R.L., "The Extra-Wehiclular Manufacture of Large Space Structures from Storable Tubular Members." in National Conference on Space Maintenance and Extra-Vehicular Activities, March 1966, page 2.8.1-2.8.35.

Summary: This simple technique for extension of long tubes from a small package has its background in the carpenters steel tape with its concave form providing rigidity. The new technique is formed similar with a tube that provides overlap thus producing a rigid, overlapping seamed tube, from a small box-like container. Concept could be used for space structures, booms, antennas, astronaut "holder," etc.

64. Schollhammer, F.R., "Electron Beam Welding for In-Space Assembly and Maintenance." in National Conference on Space Maintenance and Extra-Wehicwlar Activities, March 1966, page 2.6.1-2.6.26.

Summary: Electron beam welding is new technique. Is now finding serious consideration as the only practical means of providing in-space fabrication. Further laboratory efforts are continuing to develop a hand held electron beam gun. Objectives and problems presented in paper.

65. Schwinghamer, Robert J., "Tool Experiments for Assembly, Maintenance and Repair in Space." in National Conference on Space Maintenance and Extra-Vehicular Activities, March 1966, page 4.6.1-4.6.30 (includes 18 pictures and charts).

Summary: Pulse power concepts for tools and missiles are considered for advanced systems way beyond the state-of-the-art. Conclusions and experiments conducted for state-of-the-art.

66. Seale, L.M. and Economou, N. "EVA Space Missions, An Overview of the Requirements." Handout paper at the National Conference on Space Maintenance and EVA, March 1966, Orlando, Florida.

Sumnary: "Definition of EVA, and various approaches to EVA which exist at the present time, a delineation of the operational requirements for EVA and a description of the range of EVA hardware systems which are currently being studied."

AMU orientation using Bell experiments.

67. Seale, L.M., Economou, N., Stewart, R.A. "Remote Maneuvering Unit," in National Conference on Space Maintenance and Extra-Vehicular Activities, March 1966, page 3.3.1-3.3.17.

Sumnary: Discusses nine missions for use of RMU. The astronaut controls the RMU within close range to the spacecraft by the "outside-in" control cues he has by looking out the spacecraft window OF by the "inside-out" cues provided to him on a TV monitor from the visual cues sensed by TV camera mounted on the RMU. Operation control is provided by two three degree controllers from the parent craft table of RMU missions presented and description of operators control station.

68. Seeler, Henry W. "Underwater Pressure-Compensated Breathing Control Valves for Prolonged Water Immersion." Aerospace Medical Research Labs., Wright-Patterson AFB, Ohio. Final Report. for February 1960-June 1962, AMRL-TR-64-130. AD-611 807.

Two water-pressure-compensated breathing devices for prolonged immersion have been designed, fabricated, and tested underwater. One valve is a continuous-flow regulator and the other is a demand regulator. Both valves allow exhalation through a hose directly into the surface atmosphere for air analysis. One of the two valves has been used extensively during prolonged weightlessness simulation tests by immersion.

69. Sharp, E.D., "A Comcarison of Three Full Pressure Suits in Terms of Control Activation Time." AMRL-TR-64-126 Behavioral Science Lab., Aerospace Medical Research Lab., Wright-Patterson AFB, Ohio, Dec 1964.

Abstract: Apollo Phase B, Gemini G2C-1, and Apollo 1960 suits compared, pressurized and unpressurized. The controls used were knobs, toggle switches and push buttons (no suit appeared to be unequivocally superior). Panel layout, etc., illustrated.

70. Sharp, E.D., and Sears, C.W., "Walking Under Zero-Gravity Conditions Using Velcro Material." Aerospace Medical Division Aerospace Medical Research Labs. Wright-Patterson AFB, Ohio AMRL MEMO P-23,

Discussion of tests of walking using Velcro materials on mat and shoes and techniques used to maintain the best results as well as innovations of S's in and during the tests.

71. Simons, J.C., and Gardner, M.S., "Weightless Man - A Survey of Sensations and Performance While Free-Floating," March 1963, 71 p. AMRL-TDR-62-114, issue 18.

Abstract: The effect of surface-free work in space. To determine what techniques should be developed for orbital workers, while performing gross motor activities, S's reports and unique examples of short term weightless behavior.

72. Slysh, Paul, "Modular Assembly In Space," in National Conference on Space Maintenance and Extra-Vehicular Activities, March 1966, p. 2.9.1-2.9.12.

Summary: A method for automatic or semi-automatic structural assembly in orbit of a large parabolic antenna. Astronauts would direct or perform alignment functions, replace or repair defective parts. Consideration is mainly one of design of structural components and fasteners.

73. Streimer, I., Turner, D. P.W., and Volkmer, K., "An Investigation of the Effect of Total Simulation System Mass on Certain Human Forces Outputs in Tractionless Environment." North American Aviation Co. Space and information System Division Document No. SID65-1561.

Abstract: This study investigated certain manual force-producing capabilities of operators in a six-degrees-of-freedom simulator. The effects of delibrate alterations in the man-simulator total mass upon these output capabilities were also systematically studied. The results indicated that decrements related to bio-mechanical considerations of the task nature would appear in tractionless environments. The results also indicated that the response characteristics of the simulator tested were sufficiently sensitive to be eliminated as a factor in biasing output capabilities.

74. Streimer, I., Springer, W.E., and Tardiff, C.A., "Human Output Characteristics During Specific Task Performance in Reduced Traction Environment. Human Factors, Volume 6, April 1964, page 121-126.

Analysis of the alteration in the force and work producing characteristics of unbraced operators performing in reduced traction environment. The subjects, their work output vs. metabolic input rations were determined at various levels of stability. Increases of up to 70 percent in O_2 consumption per horsepower developed were found.

75. Streimer, I., Turner, D. P.W., and Volkmer, K., "An Experimental Study of Performance Characteristics in a Zero Potential Energy Manual Task." North American Aviation Inc., Space and Information System Division 5 November 1965.

Abstract: The findings and implications of experimental data obtained during the investigation of a flexion-extension (sawing) type task are discussed. Experimental equipment was designed with extremely low friction so as to capitalize upon the absence of potential energy similar to that of zero gravity where a fixed-man loose object relationship could be duplicated. The comparative differences of work output characteristics of efficiency, rate, and total amplitude attributable to the absence or presence of potential energy are discussed. The implications defining the maximum capabilities and minimum requirements of an operator pertorming this specific task are presented.

76. Thayer, W.S., "Human Angular Motion Capability in the Zero Gravity Environment." in Institute of Environmental Sciences, Annual Technical Meeting, 11th Chicago, Ill., April 21-23, 1965 proceedings (A65-29982 19-11.)

Discussion of tractionless experimental methods which provide an accurate simulation of true weightlessness, air bearings used.

77. Trout, O. F. Jr., "A Water Immersion Technique for the Study of Mobility of a Pressure-Suited Subject under Balanced-Gravity Contitions," NASA Langley Research Center, Langley Station, Hampton, Va., NASA TN D-3054, January 1966.

Summary: Techniques for zero gravity simulation providing degrees of freedom including test procedures. Tests showed that the water-imnersion technique is valid where velocity is low.

78. U.S. Joint Publications Research Service, 1962, "The Effect of Changes in the Gravitational Field on the Coordination of Man's Voluntary Movements." (Joint Publications Research Service, WASHDC), JPRS-15539, 2 October 1962.

Abstract: Study of the effect of changes in gravitational field on the coordination of man's voluntary movements. Limits of disturbance depends on condition and training of s's, are proportional to logarithm of acceleration of force of weight.

79. Vinograd, S.P., "Medical Experiments in Gemini," Astronautics and Aeronautics, Volume 2, November 1964, page 70-73.

Summary: Review of the basic experimental framework of the Gemini medical experiment program with description of the in-flight experiments scheduled. The major stress relates to weightlessness and combination of it with other factors. All seem to be related to direct physiological functions.

80. Boeing Company, 'Weightlessness-Underwater for Outer Space." Product Engineering, 52, 4 January 1965.

A brief article on underwater studies made by Boeing Company, Seattle, Washington. The test chamber used is 15 feet deep, 19 feet long and 14 feet wide, big enough to test mockups of proposed space vehicles. The research program is OGER (O-Gravity Effects Research).

81. Weltman, Gershon, Raymond A. Christianson and Glen H. Egstrom, "A Diver Restraint Device for Underwater Experimentation." Biotechnology Lab., University of California, Los Angeles. Report No.'s TN-30; 65-5, February 1965, 6 p. AD 463097.

There is currently a great deal of interest on many fronts concerning man's inhabitation of the sea. If this interest is a valid indication of future effort, as it seems to be, one may expect a significant increase in the number of experimental studies dealing with human work and task performance underwater. It seems reasonable to assume that the goals of these new studies will match the goals of previous investigations in other work environments. That is, there will be similar emphasis on the psycho-physiological effects of environmental variations, and on the ways in which equipment and workplace design influence performance level. For the underwater studies to be of equal practical value, however, they will also have to match the care and control of previous experimentation. This means that in many instances, because of the novel aspects of operating underwater, investigators will have to evolve, perfect, and communicate modified techniques for handling subjects, establishing work tasks, acquiring data, and so forth. Some brief remarks on the design and use of a diver restraint device applicable to several types of underwater study are presented.

82. Whiteside, T. C. D., "Hand-Eye Coordination in Weightlessness." Aerospace Medicine, 32 (8):710-725, August 1961.

To study hand-eye coordination under conditions that would eliminate the variable of visual monitoring of performance yet with eye movement controlled, S's were required to point at graph paper situated some 20 to 25 inches from his chest at chest level. A thimble with a point was worn on the index finger so that accurate measurements could be made. A mirror was located in such a manner that the S saw a target situation to one side but could not see his hand and arm. The aimimg task was performed under normal conditions, under simulation of subgravity (immersion in water up to neck), under zero g in an aircraft flying the well-known parabola, and under acceleration (29) on the centrifuge. Practical implications of the findings were indicated.

83. Whitsett, C. E., "A Mathematical Model to Represent Weightless Man." (Paper 34th Annual Meeting of the Aerospace Medical Association, Statler-Hilton Hotel, April 29, May 2, 1963)

Abstract: A mathematical model which will represent the biomechanical properties of the human body is needed. This paper describes such a model. It is concerned with only those major dynamic effects which result when the human body is subject to unbalanced forces and not to physiological or psychological problems of manned space flight.

84. Willoughby, Lt. A. J., Garnett, R. J. and Parker, F.W., "A Summary of Research as of January 1966 in Extra-Vehicular Maneuvering Techniques for Space." in National Conference on Space Maintenance and Extra-vehicular Activities, March 1966, page 3.4.1-3.4.28.

Summary: Results of researcn on extra-vehicular maneuvering performed to date by A. F., NASA, and industry. Concepts covered include manual locomotion methods, soaring, and powered maneuvering units, including automatic stabilization units. Findings and conclusions based on analysis, computer simulation, frictionless simulators, zero-g flight tests and space tests. Clarification is made of missions and innate limitations of each component.

85. Wolf, R.L., "The Use of Full Pressure Suits for Underwater Studies to Simulate Weightlessness." General Dynamics/Astronautics, San Diego, California, 1 April 1964, CDA-ERR-AM-495.

For evaluating some of the effects of a weightless environment, the approximately neutral buoyancy of the human body in water provides a suitable simulation. One of the most difficult problems in the use of full pressure garments in underwater testing is their positive buoyancy when inflated to normal pressures with air. For proper simulation it is necessary to have the underwater characteristics of the full pressure suit similar to those encountered in outer space. Any weights used to gain neutral buoyancy will add mass to particular points, making it difficult to control the center of gravity and to make normal body movements. For this test the technique of pressurizing the suit with water, although not of the most desirable quality, did provide a satisfactory means for partial simulation and gave valuable information for modification necessary for future tests.

86. Youngblood, G. J., and Davidson, J.B., "Apollo Extension Systems Conceptual Design Study of an S-IVB Orbital Workshop. Brown Engineering Co. Inc., Space Vehicle Division, Huntsville, Alabama, NASA Contract No. NAS8-20073, 30 September, 1965. (BECO 8-20073-ABX-006-2).

Summary: Feasibility study of using a spent S-IVB stage and the Apollo Command and Service Modules as an orbiting Lab and/or workshop. LH_2 tank to be vented and modified for pressurized and unpressurized occupancy. Minimum modification ground rules. Study concluded concept is feasible with considerable merit.

PART 2

1. Armsby, D. H., "Task Demand Analysis," Human Factors, Vol. 6, December 1962, pp. 381-387.

2. Balke, Bruno, "Human Tolerances," Physiology of Man in Space, New York Academic Press, Inc., 1963, pp. 149-171.

3. Baker, W. E., Mc Cleknan, L. M., Thayer, W. S., and Fine Man, H. E., "Measurements of Human Abilities to Apply Forces While Tractionless." Institute of Environmental Sciences, 1963 Annual Technical Meeting Proceedings, Mt. Prospect, Illinois, 1963, pp. 625-633.

4. Bailey, F. J., "Flight Safety Aspects of Manned Space Flight." Second manned space flight meeting, 1963, pp. 195-198.

5. Beckman, E. L., Coburn, K. R., and Chambers, R. M., "Some Physiological Changes Observed in Human Subjects During Zero "G" Simulation by Immersion in Water to Neck Level," NADC-MA-6107, Report 1, Naval Air Development Center, Johnville, Pennsylvania, Aviation Medical Acceleration Laboratories, April 10, 1961, p. 29.

6. Belasco, N., "Umbilical Lines for Extravehicular Activity," AIAA and Aerospace Med. Assoc. Manned Space Lab. Conference in Los Angeles, Paper 63147, May 2, 1963, p. 11.

7. Belasco, N., "Crew Transfer in Orbiting Space Craft," Advances in the Astronautical Sciences, Vol. 16, Part 1, Space, Rendezvous, Rescue and Recovery, Edited by Norman V. Petersen, Western Periodicals Company, North Hollywood, California, issue 24, 1963, pp. 693-726.

8. Boyrne, Geoffery H., "Neuromuscular Aspects of Space Travel," Physiology of Man in Space, Academic Press, Inc., New York, 1963, pp. 1-59. (28 Refs.)

9. Brannon, Earl W. Rockwood, Charles A., and Potts, Pauline, "The Influence of Specific Exercises in the Prevention of Debilitating Musculoskeletal Disorders, Implication in Physiological Conditioning for Prolonged Weightlessness," Aerospace Medicine, Vol. 34, October 1963, issue 24, pp. 900-906.

10. Burns, N. M., and Burdick, R. L., "Effects of Pressure Suit Inflation on Reaction Times of Project Mercury Astronauts," Vol. 32, no. 9, pp. 839-843, Aerospace Med.

11. Cacioppe, A. J. and Joppesen, M. L., "Expandable Space Stations, Implications for Prolonged Manned Space Flight," (Goodyear Aircraft Corp., Akron, Ohio), Paper, Third International Symposium on Rockets and Astronautics, September 1, 1961.

12. Celantano, J. T., and Alexander, H. S., "The Use of Hand Tools in Space--An Empirical Approach," Paper No. 61-145-1839, Institute of Aerospace Science, June 13, 1961.

13. Chaffee, John W., (Boeing Co.), "Changes in Human Center of Gravity by Changes in Direction of Acceleration." ARS Journal, Vol. 32, issue 01, November 1962, pp. 1677-1680.

14. Chkhaidze, L. V., "NASA Coordination of Arbitrary Movements of a Human Being in a Changing Gravitational Field, in its Prob. of Space Biology," November 1963, pp. 483-495.

15. Clark, J. W., "External Operations on the Manned Space Laboratory." Presented at AIAA and Aerospace Med. Association Manned Space Lab. Conference, Los Angeles, California, May 2, 1963, Paper 63146, p. 13.

16. Cohen, Leonard A., "Optimization Logistics Planning for Physiological Experiments in a Manned Space Laboratory," Am. Institute of Aeronautics and Astronautics--Aerospace Medical Association, Manned Space Laboratory Conference, Los Angeles, California, May 2, 1962, Paper 63145, p. 7.

17. Cording, C. R., "Extra-Vehicular Maintenance and Techniques," Second Manned Space Flight Meeting, New York, AIAA, 1963, pp. 86-91.

18. Crains, K. L, "The Feasibility of Manned Orbital Maintenance," 23 page NASA contract 55072, SM-41449, January 1962.

19. Creelmen, J. A., "Training for Orbital Maintenance--Mechanical Engineers, Aviation and Space, Hydraulic, and Gas Turbine Conference and Products Show," Los Angeles, California, March 3-7, 1963, Paper 63, AHGT-82, p.6.

20. Day, R. E., "Operations-Flight Crew Requirements, in its Manned Orbital Operations Spec. Section," NASA, Houston, Texas, 1963, p. 74.

21. Deutsch, S., "A Systematic H. F. Approach to the Design of Space and Weapon Systems for Maintainability." Presented at SAE National Aeron. Meeting, October 10-14, 1960, Engineering Paper 945.

22. Eggleston, J. M., "Some Abort Techniques and Procedures for Manned Spacecraft," Space Engineering, Vol. 21, November 1962, pp. 17-26.

23. Graveline, Duane E. and McCally, Michael, "Body Fluid Distribution, Implications for Zero Gravity," Aerospace Medicine, Vol. 33, November 1962, issue 04, pp. 1281-1290, (31 Refs.).

24. Hunsicker, Paula, "Arm Strength at Selected Degrees of Elbow Flexion," WADC-TR 54-548, 1955, p.66, (165 Refs.).

25. Kama, W. N., "Effects of Simulated Weightlessness upon Positioning Responses," December 1961, p. 17. Aerospace Med. Research Labs. Aeronautical Systems Div. Wright-Patterson AFB, Ohio. ASD-TR-61-555.

26. Kasten, D. F., "Human Performance in Short Orbital Transfer," Aerospace Med., Vol. 34, March 1963, pp. 201-208.

27. Keller, T., and Hagan, J. T., "Vehicular Control Using the Human Balance Reflex," AIAA Simulation for Aerospace Flight Conference, Columbus, Ohio, August 26-28, 1963, N. Y.

28. Kennedy, K., "Human Mechanics, Four Monographs Abridged," Behavioral Science Lab., Wright-Patterson AFB, Ohio, AMRL-TDR-63-123, 1963.

29. King, Barry G., and Mans, Mitchell C., "The Feasibility of Estimating the Energy Expenditure of Astronauts Through Partial Simulation of Weightlessness," Operations Research Inc., Silver Springs, Md, Tech. Report' No. 170, February 2, 1962, p. 52.

30. Krogmen, W. M, and Johnson, F. E, "Human Mechanics," AMRL TDR 63-123, Air Force System Command, December 1963.

31. Kulwicki, P. V., and Peoples, G., "Controlled Rotation and Stabilization for Orbital Worker," AMRL-MEMO, December 1962, p. 21.

32. Lawton, Richard W., and McCally, Michael, "The Pathophysiology of Disuse and the Problem of Prolonged Weightlessness," AMRL-TDR-63-3, June 1963, p. 51, (169 Refs.).

33. Loftus, J. P., Lt., "Weightlessness and Performance, A Review of the Literature," Behavioral Science Lab., Aeronautical Systems Div., Wright-Patterson AFB, Ohio, ASD TR 61-116, June 1961.

34. Marton, Dr. T., and Merritt, A. H., "The Use of Neutral Buoyancy Submersion as an Aid to Study of Human Performance in Zero Gravity," General Electric Co., Missile and Space Division, King of Prussia, Pennsylvania.

35. Mueller, Don D., "Zero Gravity Indoctrination for the Gemini/ Apollo Astronauts," AMRL-MEMO, March 1963, p. 31, Aerospace Med. Div., Aerospace Med. Res. Labs., Wright-Patterson AFB, Ohio.

36. Mathews, Charles W., "U.S. Experience on the Utilization of Man's Capabilities in Space Environment in Comm. on Space Res.," NASA, Life Science and Space Res., 1963, pp. 141-159.

37. Edson, James B., "Physical Sciences Research Program in a Manned Orbiting Laboratory." Presented at the AIAA and Aerospace Med. Assoc. Manned Space Lab. Conference, Los Angeles, California, NASA, AIAA Paper 63-135, May 2, 1963.

38. Gerathewohl, S. J., "Operational Aspects of Weightlessness, Proc. of the Lunar and Planetory Exploration Collection," Santa Monica, California, May 23-24, 1962, pp. 141-145. NASA

39. Nordby, Frederick J., "Preparation for Lunar Environment with Means of Varying Gravitational Environment," Society of Automotive Envineers, National Aeronautic and Space Engineering and Manufacturing Meeting, Los Angeles, California, September 23-27, 1963, Paper 758 A, p. 4

40. Peters, J. M., "Analysis of Space Missions in Relation to Task Performance of Crew and Duration of Mission," in 12th International Astronautical Congress Procedings, Vol. 2, Washington, D.C., October 1-7, 1961, New York and London Press Inc., 1963, pp. 625-635.

41. Pierce, B. F., and Casco, E. L., "Crew Transfer in Zero-G as Simulated by Water Immersion," G D/A-ERR-AN-502, General Dynamics, Astonautics, April 15, 1964.

42. Powe, W. E., and Bailey, W. E., "Manned Maintenance of Space Vehicles," Advances in the Astronautical Sciences, Vol. 16, Part 1, Space Rendezvous, Rescue and Recovery, Edited by Norma V. Petersen, Western Periodicals Co., North Hollywood, California, 1963, pp. 476-494.

43. Sanders, H. C., "The Effects of Man on the Weight of a Manned Space Vehicle," Advances in the Astronautical Sciences, Vol. XI, Edited by Jacobs, H., Western Periodicals, North Hollywood, California, 1963, pp. 227-270.

44. Santschi, W. R., DuBois, J., and Omoto, C., "Moments of Inertia and Centers of Gravity of the Living Human Body," AMRL-TDR-63-36, May 1963, p. 65, (11 Refs.).

45. Simons, J. C., "Walking Under Zero-Gravity Conditions," WADC TR-59-327, issue 99, October 1959, p. 12.

46. Simons, J. C., and Gardner, M. S., "Self-Maneuvering for the Orbital Worker," WADD TR-60-748, December 1960, 28 A.

47. Simons, J. C., Walk, D., and Sears, C. W., "Motion Performance of Pressure-Suited Subjects Under Zero and Lunar Gravity Conditions," AMRL-TDR-64.

48. Smedal, H. A., et. al., "Crew Physical Support and Restraints in Advanced Manned Flight Systems," J. Am. Rocket Soc., issue 2 November 1961, p.5.

49. Space Science Board, "Working Group on Problems of Weightlessness in Space Flight," National Academy of Science, Washington, D.C., April 1963, p. 56.

50. Springer, W. E., Stephens, T. L., and Streimer, I., "The Metabolic Cost of Performing Specific Exercise in a Low-Friction Environment," Aerospace Medicine, issue 19, Vol. 34, June 1963, pp. 486-488.

51. Stone, R. W., Jr., and Letko, W., "The Effects of Angular Motion of Rotating Space Vehicles on the Ability of an Astronaut to Perform Simple Tasks," NASA, Langley Research Center, Langley, Virginia, 1962, p. 25. For presentation at the Annual Meeting of the Inst. of Environmental Sciences, Chicago, Illinois, April 10-13, 1962.

52. Stone, R. W., Jr., and Letko, W., "Some Observations During Weightlessness Simulation with Subjects Immersed in a Rotating Water Tank," NASA TND-2195, 1964.

53. Swearingen, John J., "Determination of Centers of Gravity of Man," Civil Aeromedical Research Inst., Aeronautical Center, Oklahoma City, Oklahoma, Report 62-14, August 1962, p. 39, (Refs. 2).

54. Von Beckh, H. J., "A Summary of Motion Sickness Experiences in Weightless Flight," Aerospace Med. Div., Wright-Patterson AFB, Ohio. Symposium on Motion Sickness with Special Reference to Weightlessness, June 1963, pp. 67-72.

55. Wade, J. E., "Psychomotor Performance Under Conditions of Weightlessness," MRL-TDR-62-73, June 1959, August 1960.

56. Warzecha, L. W., and Merrick, E. J., "Criteria and Techniques for Maintenance, Repair, and Assembly in Manned Orbital Operations." Presented at the IAS National Summer Meeting, Los Angeles, California, June 19-22, 1962, IAS Paper 66-136.

57. Whitsett, C. E., Jr., "Some Dynamic Response Characteristics of Weightless Man," AMRL-TDR-63-18, issue 19, April 1963, p. 56.

58. Wolf, R. L., "The Use of Full Pressure Suits for Underwater Studies to Simulate Weightlessness," GD/A-ERR-AN-495, General Dynamics, Astronautics, January 1, 1965.

59. Wunder, C., "A Survey of Chronic Weightlessness Simulation in Biological Research," HQ ARDC TDR 64-1, State University of Iowa.

60. Yeremin, A. V. (USSR), "Man's Capacity to Work in a State of Weightlessness," NASA no. N65-27032, U.S. Dept. of Commerce, clearing house for Fed. Scientific and Tech. information, Joint publication research service, Washington, D.C., June 1965.

61. Yuganov, Ye. M., "Some Human Reactions Under Subgravity Conditions." Joint publications research service, Washington, D.C., in its Problems of Space Biol., MR.72, 1963, pp. 219-228. Presented at 10th European Congress of Aviation and Space Medicine, Paris, September 26-30, 1961.

62. Zhuravley, B. A., "Re-Organization of Motor Habits in the State of Weightlessness," Joint publications research service, Washington, D.C., in its Problems of Space Biol., March 27, 1963, pp. 235-239.

63. "Human Factors for Extra-vehicular Space Environment—Human Adaptive Capacity and Necessary Equipment," Library of Congress, no. A 64-80816.

64. "Pressure Suit Wearing Effect on Rate, Amplitude, and Efficiency of Work in Normal and Reduced Traction Environment," AIAA no. A 64-22815.

65. "Tools for Space," Machine Design, Vol. 34, November 22, 1962, pp. 134-138.

66. "Weightlessness--Underwater For Outer Space," Product Engineering 52, January 4, 1965.

1. Graveline, D. E., and Barnard, G. W., Aerospace Medicine 32:726, 1961.

2. Graybiel, A. and Clark, B., Aerospace Medicine, 32:181, 1961.

3. Birkhead, N. C., Blizzard, J. J., Daly, J. W., Haupt., G. J., Issekutz, B., Jr., Myers, R. M., and Rodahl, K., Technical Documentary Report, AMRL-TDR-63-37, May 1963.

4. Deitrick, J. E., Whedon, G. D., and Shorr, E., American Journal of Medicine, 4:3, 1948.

5. Taylor, H. L., Erickson, L., and Keys, A., American Journal of Physiology, 135:557, 1942.

6. Irving, L., Scholander, P. F., and Grinell, S. N., American Journal of Physiology, 135:557, 1942.

7. Johansen, K. and Krog, J. Acta physiol. Scand., 46:194, 1959.

8. Scholander, P. F., Hammel, H. T., LeMessurier, D. H., Hemningsen, E., and Garey, W., J. Appl. physiol. 17:184, 1962.

9. Peterson, L. H., Proceedings of the Second Symposium - Underwater Physiology, NAS-NRC publication 1181. Washington, 1963, pp. 267-270.

10. Irving, L., J. Appl. Physiol., 18:489, 1963.

11. Olsen, C. R. Fanestil, D. D., and Scholander, P. F., J. Appl. Physiol. 17:461, 1962.

12. Craig, A. B., Jr., Journal of Applied Physiology, 18:854, 1963,

13. Wolf, S., Trans. Am. Clin. Climat. Assoc., 76:192, 1964.

14. Tuttle, W. W., and Templin, J. L., J. Lab. Clin. Med., 28:271, 1942.

15. Keatinge, W. R., and Evans, M., Quart. J. Expt'l Physiol., 46:83, 1961.

16. Leivestad, H., Andersen, H., and Scholander, P. F., Science, 126:505, 1957.

17. Roddie, I. C., and Shepherd, J. T., Clin. Sci., 15:433, 1956.

18. Beakonsfield, P. G. J., J. Physiol. 130:467, 1955.

19. U.S. Navy Diving Manual, Part 1, NAV SHIPS 250-538, July 1963. Navy Department, Washington, D.C.

20. Craig, A. B., Jr., J. Appl. Physiol., 16:583, 1961.

1. Granville, P. S., "The Calculation of the Viscous Drag of Bodies of Revolution," David W. Taylor Model Basin Report 849 (NS 715-102), July 1953.

2. Hanavan, E. P., Jr., "A Mathematical Model of the Human Body," AMRL-TR-64-102, October 1964.

3. Binder, R. C., "Fluid Mechanics," Prentice-Hall, New York, 3rd ed., 1955.

4. Trout, O. F., Jr., Loats, H. L., Jr., and Mattingly, "A Water-Immersion Technique for the Study of Mobility of a Pressure-Suited Subject Under Balanced-Gravity Condition," NASA TND-3054, January 1966.

5. Hoerner, S. F., "Fluid-Dynamic Drag," Published by the author, 148 Busteed Drive, Midland Park, New Jersey, 1958.

6. Schmitt, T. J., "Wind-Tunnel Investigation at Air Loads on Human Beings," Report 892 (Aero 858), David W. Taylor Model Basin, Navy Dept., January 1954.

PART 5

1. Edwards, D. K., Stauffer, E. J., Pine, A., Belton, N. J., and Wortz, E. C., "Study of Astronaut Capabilities to Perform Extravehicular Maintenance Functions and Assembly in Weightless Condition:' AiResearch Report LS-166, December 1965.

2. Wortz, E. C., "Monthly Letter Report No. 2, NASA Contract NAS 1-5875, May 1966, pp. 1-6.

3. Pao, Y. C., "Mathematical Model Analysis of Underwater Simulation of Extravehicular Activies in Space," AiResearch Report LS 66-0794.

4. Trout, O. F., Jr., Loats, H. L., Jr., and Mattingly, G. S., "Study of Mobility of a Pressure-Suited Subject Under Balanced-Gravity Conditions," NASA TN D-3054, January 1966.

5. Gers, D. R., "Power and Efficiency of Large Salt-Water Fish," Aeronautical Engineering Review, January 1952, pp. 10-15.

6. Hoerner, S. F., "Fluid-Dynamic Drag," Published by Author, 148 Busteed Drive, Midland Park, New Jersey, 1958.

7. Instruction Manual, Systrac Model 160E3, "Data Acquisition System, Volume I," Systron Donner Corporation, Concord, California.

PART 6

1. Fleishman, E. A., "Development of a Behavior Taxonomy for Describing Human-Tasks," J. Appl. Psych., Vol. 51, 1967, 1-10.

2. Fleishman, E. A., and Hempel, W. E, "A Factor Analysis of Dexterity Tests," Personal Psychology, 1954, 7, 35-32. (a).

3. Fleishman, E. A., and Hempel, W. E., "Changes in Factor Structure of a Complex Psychomotor Test as a Function of Practice," Psychometrika, 1954, 18, 239-252.

4. Fleishman, E. A., The Structure and Measurement of Physical Fitness, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1964.

5. Fleishman, E. A., " 'Comments on Professor Jones' " in Bilodeau, Edward A. (ed.). Acquisition of Skill. Academic Press, New York, 1966.

6. Jones, Marshall B., "Individual Differences" in Bilodeau, Edward A. (ed.). Acquisition of Skill. Academic Press, New York, 1966.

7. Laban, Rudolf and Lawrence, F. C., Effort. Macdonald and Evans, London, 1947.

8. Melton, Arthur W., Categories of Human Learning, Academic Press, New York, 1962.

9. Smith, Karl U., "Cybernetic Theory and Analysis of Learning," in Bilodeau, Edward A. (ed.), Acquisition of Skill. Academic Press, New York, 1966.

10. Stolurow, Laurence M, "A Taxonomy of Learning Task Characteristics," AMRL-TDR-64-2, 1964.

APPENDIX D

MATHEMATICAL MODEL ANALYSIS

Part 1. Vector Manipulations

Part 2. Program Statement Listings

Part 3. Flow Charts

Derivation of Eq. (1-32)

$$\bar{V}_x = \bar{V}_A + \bar{\omega} \times \bar{r}'$$

$$= \bar{V}_A + \frac{x}{\ell}\,\bar{\omega} \times \bar{x}_{AB}$$

$$= \frac{x}{\ell}\left(\frac{\ell}{x}\bar{V}_A + \bar{\omega} \times \bar{x}_{AB}\right)$$

$$= \frac{x}{\ell}\left[\frac{\ell - x}{x}\bar{V}_A + \left(\bar{V}_A + \bar{\omega} \times \bar{x}_{AB}\right)\right]$$

$$= \frac{\ell - x}{\ell}\bar{V}_A + \frac{x}{\ell}\bar{V}_B \qquad \text{(D-1)}$$

$$\left(\frac{E_D}{\Delta t}\right)_j = \frac{\rho}{2\ell} C_D \int_0^\ell w(x)\, \|\bar{V}_x\|^2 \|\bar{V}_x \times \bar{x}_{AB}\|\, dx$$

$$= \frac{\rho C_D}{2\ell}\int_0^\ell w(x) \left(\bar{V}_x \cdot \bar{V}_x\right) \|\bar{V}_x \times (\bar{x}_B - \bar{x}_A)\|\, dx$$

$$= \frac{\rho C_D}{2\ell}\int_0^\ell w(x) \cdot \left(\frac{\ell - x}{\ell}\bar{V}_A + \frac{x}{\ell}\bar{V}_B\right) \cdot \left(\frac{\ell - x}{\ell}\bar{V}_A + \frac{x}{\ell}\bar{V}_B\right) \cdot$$

$$\cdot \left\{\left[\left(\frac{\ell - x}{\ell}\bar{V}_A + \frac{x}{\ell}\bar{V}_B\right) \times (\bar{x}_B - \bar{x}_A)\right]\right.$$

$$\left. \cdot \left[\left(\frac{\ell - x}{\ell}\bar{V}_A + \frac{x}{\ell}\bar{V}_B\right) \times (\bar{x}_B - \bar{x}_A)\right]\right\}^{\frac{1}{2}} dx$$

$$\text{(D-2)}$$

$$\left(\frac{E_D}{\Delta t}\right)_j = \frac{\rho C_D}{2\ell}\int_0^{\ell} w(x)\Big\{\left(\frac{\ell-x}{\ell}\right)^2(\bar{V}_A\cdot\bar{V}_A)+2\,\frac{(\ell-x)x}{\ell^2}(\bar{V}_A\cdot\bar{V}_B)$$

$$+\left(\frac{x}{\ell}\right)^2(\bar{V}_B\cdot\bar{V}_B)\Big\}\Big\{\left(\frac{\ell-x}{\ell}\right)^2\|(\bar{V}_A\times\bar{X}_{AB})\|^2$$

$$+2\,\frac{(\ell-x)x}{\ell^2}\left[(\bar{V}_A\times\bar{X}_{AB})\cdot(\bar{V}_B\times\bar{X}_{AB})\right.$$

$$+\left(\frac{x}{\ell}\right)^2\|(\bar{V}_B\times\bar{X}_{AB})\|^2\Big\}^{\frac{1}{2}}dx \qquad \text{(D-3)}$$

If written in the form of

$$\left(\frac{E_D}{\Delta t}\right)_j = \frac{\rho C_D}{2\ell}\int_0^{\ell} w(x)(Ax^2+Bx+C)\sqrt{ax^2+bx+c}\;dx \qquad \text{(D-4)}$$

then the abbreviations are

$$A = \frac{1}{\ell^2}(\bar{V}_A\;\bar{V}_A) - \frac{2}{\ell^2}(\bar{V}_A\cdot\bar{V}_B)+\left(\frac{1}{\ell}\right)^2(\bar{V}_B\cdot\bar{V}_B)$$

$$= \frac{1}{\ell^2}\left[(\bar{V}_A-\bar{V}_B)\cdot(\bar{V}_A-\bar{V}_B)\right] = \frac{1}{\ell^2}\|\bar{V}_{BA}\|^2 \qquad \text{(D-5)}$$

$$B = \frac{1}{\ell}\left[-2(\bar{V}_A\cdot\bar{V}_A)+2(\bar{V}_A\cdot\bar{V}_B)\right]$$

$$= -\frac{2}{\ell}\,\bar{V}_A\cdot(\bar{V}_A-\bar{V}_B) = -\frac{2}{\ell}(\bar{V}_A\cdot\bar{V}_{BA}) = \frac{2}{\ell}\,\bar{V}_A\cdot\bar{V}_{AB}$$

(D-6)

$$C = (\bar{V}_A\cdot\bar{V}_A) = \|\bar{V}_A\|^2 \qquad \text{(D-7)}$$

$$a = \frac{1}{\ell^2} \| (\overline{V}_A \times \overline{x}_{AB}) \|^2 - \frac{2}{\ell^2} (\overline{V}_A \times \overline{x}_{AB}) \cdot (\overline{V}_B \times \overline{X}_{AB})$$

$$+ \frac{1}{\ell^2} \| (\overline{V}_B \times \overline{X}_{AB}) \|^2$$

$$= \frac{1}{\ell^2} \| (\overline{V}_A \times \overline{x}_{AB}) - (\overline{V}_B \times \overline{x}_{AB}) \|^2$$

$$= \frac{1}{\ell^2} \| \overline{V}_{BA} \times \overline{X}_{AB} \|^2 \qquad \text{(D-8)}$$

$$b = -\frac{2}{\ell} \left\{ \| \overline{V}_A \times \overline{x}_{AB} \|^2 - (\overline{V}_A \times \overline{x}_{AB}) \cdot (\overline{V}_B \times \overline{x}_{AB}) \right\}$$

$$= -\frac{2}{\ell} \left\{ (\overline{V}_A \times \overline{x}_{AB}) \cdot \left[(\overline{V}_A \times \overline{x}_{AB}) - (\overline{V}_B \times \overline{x}_{AB}) \right] \right\}$$

$$= -\frac{2}{\ell} (\overline{V}_A \times \overline{x}_{AB}) \cdot (\overline{V}_{BA} \times \overline{x}_{AB})$$

$$= \frac{2}{\ell} (\overline{V}_A \times \overline{x}_{AB}) \cdot (\overline{V}_{AB} \times \overline{X}_{AB}) \qquad \text{(D-9)}$$

$$c = \| \overline{V}_A \times \overline{x}_{AB} \|^2 = (\overline{V}_A \times \overline{X}_{AB}) \cdot (\overline{V}_A \times \overline{X}_{AB}) \qquad \text{(D-10)}$$

with

$$\overline{X}_{ij} = \overline{X}_j - \overline{X}_i \qquad \text{(D-11)}$$

$$\overline{V}_{mn} = \overline{V}_n - \overline{V}_m \qquad \text{(D-12)}$$

$$\bar{V}_{BA} = \bar{V}_A - \bar{V}_B \qquad \bar{x}_{AB} = \bar{x}_B \ \bar{x}_A$$

$$\bar{V}_{BA} \times \bar{x}_{AB} = \begin{vmatrix} \bar{i} & \bar{j} & \bar{k} \\ V_{BAx} & V_{BAy} & V_{BAz} \\ x_{ABx} & x_{ABy} & x_{ABz} \end{vmatrix} = \left(V_{BAy} x_{ABz} - V_{BAz} x_{ABy}\right)\bar{i}$$

$$+ \left(V_{BAz} x_{ABx} - V_{BAx} x_{ABz}\right)\bar{j}$$

$$+ \left(V_{BAx} x_{ABy} - V_{BAy} x_{ABx}\right)\bar{k}$$

$$\bar{V}_A \times \bar{X}_{AB} = \left(V_{Ay} x_{ABz} - V_{Az} x_{ABy}\right)\bar{i}$$

$$+ \left(V_{Az} x_{ABx} - V_{Ax} x_{ABz}\right)\bar{j} + \left(V_{Ax} x_{ABy} - V_{Ay} x_{ABx}\right)\bar{k}$$

$$\left(\bar{V}_A \times \bar{x}_{AB}\right) \cdot \left(\bar{V}_{AB} \times \bar{x}_{AB}\right) = \left(V_{Ay} x_{ABz} - V_{Az} x_{ABy}\right)\left(V_{BAz} x_{ABy} - V_{BAy} x_{ABz}\right)$$

$$+ \left(V_{Az} x_{ABz} - V_{Ax} x_{ABz}\right)\left(V_{BAx} x_{ABz} - V_{BAz} x_{ABx}\right)$$

$$+ \left(V_{Ax} x_{ABy} - V_{Ay} x_{ABx}\right)\left(V_{BAy} x_{ABx} - V_{BAx} x_{ABy}\right)$$

W(x) of Torso

Referring to Fig. (3-10).

$$W(x) = S_3 \sin\phi + S_1 \cos\phi \qquad (0-13)$$

$$\overline{X}_{12} = \overline{X}_2 - \overline{X}_1 \qquad (0-14)$$

$$\overline{V}_x = \frac{S_2 - x}{S_2}\, \overline{V}_0 + \frac{x}{S_2}\, \overline{V}_3$$

$$= \frac{S_2 - x}{2 S_2}\left(\overline{V}_1 + \overline{V}_2\right) + \frac{x}{S_2}\, \overline{V}_3 \qquad (D-15)$$

$$\overline{V}_{xc} = \overline{V}_x \sin\theta \qquad (D-16)$$

$$\cos\phi = \frac{\| \overline{X}_{12} \cdot \overline{V}_{xc} \|}{\| \overline{X}_{12} \| \, \| \overline{V}_{xc} \|}$$

$$= \frac{\| \overline{X}_{12} \cdot \overline{V}_x \sin\theta \|}{S_3 \, \| \overline{V}_x \sin\theta \|}$$

$$= \frac{\| \overline{X}_{12} \cdot \overline{V}_x \|}{S_3 \, \| \overline{V}_x \|} \qquad (0-17)$$

W(x) of Limbs

Upper Arms : $x = 0$ at joints 1 and 2

$$W(x) = D_{AU} - \frac{x}{S_{AU}}\left(D_{AU} - D_{Am}\right) \qquad (0-18)$$

Lower Arms : $x = 0$ at joints 4 and 5

$$w(x) = D_{AM} - \frac{x}{S_{AL}} (D_{AM} - D_{AL}) \tag{D-19}$$

Upper Legs : $x = 0$ at joint 3

$$w(x) = D_{LU} - \frac{x}{S_{LU}} (D_{LU} - D_{LM}) \tag{D-20}$$

Lower Legs : $x = 0$ at joints 8 and 9

$$w(x) = D_{LM} - \frac{x}{S_{LL}} (D_{LM} - D_{LL}) \tag{D-21}$$

Glove :

$$\bar{x}_H = \bar{x}_4 + \bar{x}_{4H} = \bar{x}_4 + \frac{S_{AL} + \frac{1}{2} D_H}{S_{AL}} \bar{x}_{46} \tag{D-22}$$

$$\begin{aligned}
\bar{V}_{H4} &= \bar{V}_4 + \bar{\omega}_4 \times \bar{x}_{4H} \\
&= \bar{V}_4 + \bar{\omega}_4 \times \left(\frac{S_{AL} + \frac{1}{2} D_H}{S_{AL}} \bar{x}_{46} \right) \\
&= \frac{S_{AL} + \frac{1}{2} D_H}{S_{AL}} \left(\bar{V}_4 + \bar{\omega}_4 \times \bar{x}_{46} \right) - \frac{D_H}{2 S_{AL}} \bar{V}_4 \\
&= \left(1 + \frac{D_H}{2 S_{AL}} \right) \bar{V}_6 - \frac{D_H}{2 S_{AL}} \bar{V}_4
\end{aligned} \tag{D-23}$$

$$A_1 = \frac{1}{4} \pi D_H^2 \tag{D-24}$$

$$\bar{V}_{H5} = \left(1 + \frac{D_H}{2 S_{AL}} \right) \bar{V}_7 - \frac{D_H}{2 S_{AL}} \bar{V}_5 \tag{D-25}$$

Shoulder Front Area

Torso :

$$\bar{V}_{on} = \bar{V}_o \cos\theta = \bar{V}_o \frac{\| \bar{V}_o \cdot \bar{X}_{o3} \|}{S_2 \| \bar{V}_o \|} \qquad \text{(D-26)}$$

$$\bar{X}_{o3} = \bar{X}_3 - \bar{X}_o = \bar{X}_3 - \frac{1}{2}(\bar{X}_1 + \bar{X}_2) \qquad \text{(D-27)}$$

$$\bar{V}_o = \frac{1}{2}(\bar{V}_1 + \bar{V}_2) \qquad \text{(D-28)}$$

$$A_{xn} = S_1 S_3 \qquad \text{(D-29)}$$

Upper Arms : $i = 1$ and 2

$$\bar{V}_{in} = \bar{V}_i \cos\theta = \bar{V}_i \frac{\| \bar{V}_i \cdot \bar{X}_{i,i+3} \|}{S_{AU} \| \bar{V}_i \|} \qquad \text{(D-30)}$$

$$A_{in} = \frac{1}{4} \pi D_{AU}^2 \qquad \text{(D-31)}$$

Helmet:

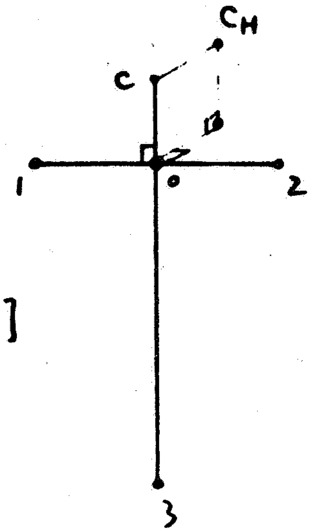
$$\bar{x}_{3o} = \bar{x}_o - \bar{x}_3 = \tfrac{1}{2}(\bar{x}_1 + \bar{x}_2) - \bar{x}_3$$

$$\bar{x}_{oc} = \frac{D_{HM}}{2S_2}\,\bar{x}_{3o}$$

$$\bar{x}_c = \bar{x}_o + \bar{x}_{oc}$$

$$= \tfrac{1}{2}(\bar{x}_1 + \bar{x}_2) + \frac{D_{HM}}{2S_2}\left[\tfrac{1}{2}(\bar{x}_1 + \bar{x}_2) - \bar{x}_3\right]$$

$$= \tfrac{1}{2}\left(1 + \frac{D_{HM}}{2S_2}\right)(\bar{x}_1 + \bar{x}_2) - \frac{D_{HM}}{2S_2}\bar{x}_3$$



$10 = 02 = \tfrac{1}{2} S_3$

$oc = cc_H = \tfrac{1}{2} D_{HM}$

$o3 = S_2$

$$\bar{x}_{C_H} = \bar{x}_c + \bar{x}_{cc_H}$$

$$= \bar{x}_c + \frac{\bar{x}_{12} \times \bar{x}_{o3}}{S_2 S_3} \cdot \tfrac{1}{2} D_{HM}$$

$$= \tfrac{1}{2}\left(1 + \frac{D_{HM}}{2S_2}\right)(\bar{x}_1 + \bar{x}_2) - \frac{D_{HM}}{2S_2}\bar{x}_3 + \frac{D_{HM}}{2S_2S_3}(\bar{x}_2 - \bar{x}_1) \times \left(\bar{x}_3 - \tfrac{1}{2}\bar{x}_1 - \tfrac{1}{2}\bar{x}_2\right) \tag{D-32}$$

Solve for $\bar{\omega}_1$ from

$$\bar{V}_2 = \bar{V}_1 + \bar{\omega}_1 \times \bar{x}_{12} \tag{D-33}$$

$$\|\bar{V}_{C_H}\| = \|\bar{V}_1 + \bar{\omega}_1 \times \bar{x}_{1C_H}\| \tag{D-34}$$

$$A_H = \tfrac{1}{4}\pi D_{HM}^2 \tag{D-35}$$

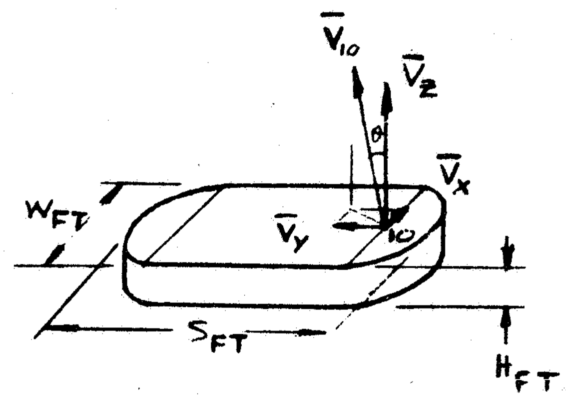
× 8

Boot

$$A_x = S_{FT} \cdot H_{FT}$$

$$A_Y = W_{FT} \cdot H_{FT}$$

$$A_Z = \left(S_{FT} W_{FT} - \frac{\pi}{4} W_{FT}^2 \right) - \frac{\pi}{4} D_{LL}^2$$



$$\bar{V}_Z = \bar{V}_{10} \cos\theta = \bar{V}_{10} \left| \frac{\bar{V}_{10} \cdot \bar{X}_{8\,10}}{\| \bar{V}_{10} \| \, \| \bar{X}_{8,10} \|} \right|$$

$$\| \bar{V}_Z \| = \left| \frac{\bar{V}_{10} \cdot \bar{X}_{8\,10}}{\| \bar{X}_{10} - \bar{X}_8 \|} \right| \tag{D-36}$$

$$\bar{V}_X = 0 \quad \text{(approximated)}$$

$$\| \bar{V}_Y \| = \sqrt{\| \bar{V}_{10} \|^2 - \| \bar{V}_Z \|^2} \tag{D-37}$$

(Replacing subscripts 8, 10 by 9 11 to obtain formulas for left boot.)

PART 2. Program Statement Listings

```
*      JOB        X0620      Y.C. PAO
C
C      UNDERWATER SIMULATION OF ASTRONAUT EXTRAVEHICULAR ACTIVITIES
C
       EQUIVALENCE (V,A)
       DIMENSION A(3,11,100),AL(3,9),AS(3,9),C(3,4),COEF(101),DT(100),
      *          T1(3),T2(3),T3(3),VO(3,11),XO(3,11),XMBRT(100)
       DIMENSION FL(9),S(4),V(3,11,100),X(3,11,100)
       COMMON V,X
       COMMON ISEG,ITIMF
       COMMON DAL,DAM,DAU,DLL,DLM,DLU,FL,S
C
C      INITIALIZATION OF DATA
C
       PI=3.14159
       RHO= 1.94
   10  READ INPUT TAPE 41,12,
      1                       ANKC,CHESB,CHESD,ELBWC,FISTC,HFT,HLW,HMC,SAL,
      2                       SAU,SFT,SLL,SLU,STS,THIHC,TOEW,UARMC,WAISO,
      3                       WRISC,XNEEC
       READ INPUT TAPE 41,12,DTK,BTK,HTK
       DO 11 II=1,11
   11  READ INPUT TAPE 41,12,(VO(K,II),K=1,3),(XO(K,II),K=1,3)
       READ INPUT TAPE 45,15,NDT
       READ INPUT TAPE 45,12,(DT(K),K=1,NDT)
       READ INPUT TAPE 41,12,(XMBRI(K),K=1,NDT)
       READ INPUT TAPE 45,12,(((A(I,J,K),K=1,NDT),J=1,11),I=1,3)
       CALL VANOX(A,VO,XO,DT,NDT,V,X)
   12  FORMAT(10F8.2)
   15  FORMAT(16I5)
C
C      CENFRATE SEGMENT MODELS
C
       S(1)=CHESD+DTK
       S(2)=.5*(STS+HTK)
       S(3)=.5*(CHESB+BTK)
       S(4)=CHESD
       DHM=HMC/PI
       DAU=UARMC/PI
       DAM=ELBWC/PI
       DAL=WRISC/PI
       DH=FISTC/PI
       DLU=THIHC/PI
       DLM=XNEEC/PI
       DLL=ANKC/PI
       WFT=.5*(TOEW+HLW)
       FL(1)=STS
       FL(2)=SAU
       FL(3)=FL(2)
       FL(4)=SAL
       FL(5)=FL(4)
       FL(6)=SLU
       FL(7)=FL(6)
       FL(8)=SLL
       FL(9)=FL(8)
```

```
      AARM=.25*PI*DAU**2
      AXN=S(1)*S(3)
      AGLOV=.25*PI*DH**2
      AHM=.25*PI*DHM**2
      AYBT=WFT*HFT
      AZBT=SFT*WFT-.25*PI*(WFT**2+DLL**2)
      C1=DH*.5/FL(4)
      C2=1.+C1
C
C     ENERGY CONSUMPTION ON DRAG
C
      ED=0.
      TIME=0.
      DO 80 IT=1,NDT
      TIME=TIME+DT(IT)
      ITIME=IT
      CDX=CD(ITIME)
      CONST=.5*RHO*CDX*DT(IT)
      CALL ABC(AL,AS)
C
C     1. LIMBS, TORSO AND BACK-PACKED BOX
C
      DO 70 IS=1,9
      ISEG=IS
      KK=IS+IT
      CALL SIMPN(FL(IS),21,KK,COEF,AL(IS),AS(IS),SUM)
      ED=ED+SUM*CONST/FL(IS)
   70 CONTINUE
C
C     2. HELMET, GLOVES, BOOTS AND SHOULDER FRONTAL AREA
C
      DO 30 J1=1,3
      T1(J1)=X(J1,2,ITIME)-X(J1,1,ITIME)
   30 T2(J1)=X(J1,3,ITIME)-.5*(X(J1,1,ITIME)+X(J1,2,ITIME))
      T3(1)=T1(2)*T2(3)-T1(3)*T2(2)
      T3(2)=T1(3)*T2(1)-T1(1)*T2(3)
      T3(3)=T1(1)*T2(2)-T1(2)*T2(1)
      A1=.5*DHM/S(2)
      A2=.5*(1.+A1)
      A3=A1/S(3)
      DO 34 J2=1,3
      T2(J2)=A2*(X(J2,1,ITIME)+X(J2,2,ITIME))-A1*X(J2,3,ITIME)+
     *        A3*T3(J2)-X(J2,1,ITIME)
      C(J2,4)=V(J2,2,ITIME)-V(J2,1,ITIME)
   34 C(J2,J2)=0.
      C(1,2)=T1(3)
      C(1,3)=-T1(2)
      C(2,1)=-T1(3)
      C(2,3)=T1(1)
      C(3,1)=T1(2)
      C(3,2)=-T1(1)
      CALL EQSOL(C,3,T1)
      VCHM=SQRTF((V(1,1,ITIME)+T2(3)*T1(2)-T2(2)*T1(3))**2+
     1           (V(2,1,ITIME)-T2(3)*T1(1)+T2(1)*T1(3))**2+
     2           (V(3,1,ITIME)+T2(2)*T1(1)-T2(1)*T1(2))**2)
```

```
      V1NM=ABSF(V(1,1,ITIME)*(X(1,4,ITIME)-X(1,1,ITIME))+V(2,1,ITIME)*
     1         (X(2,4,ITIME)-X(2,1,ITIME))+V(3,1,ITIME)*(X(3,4,ITIME)-
     2         X(3,1,ITIME)))/FL(1)
      V2NM=ABSF(V(1,2,ITIME)*(X(1,5,ITIME)-X(1,2,ITIME))+V(2,1,ITIME)*
     1         (X(2,5,ITIME)-X(2,2,ITIME))+V(3,2,ITIME)*(X(3,5,ITIME)-
     2         X(3,2,ITIME)))/FL(2)
      VH4M=SQRTF((C2*V(1,6,ITIME)-C1*V(1,4,ITIME))**2+
     1          (C2*V(2,6,ITIME)-C1*V(2,4,ITIME))**2+
     2          (C2*V(3,6,ITIME)-C1*V(3,4,ITIME))**2)
      VH5M=SQRTF((C2*V(1,7,ITIME)-C1*V(1,5,ITIME))**2+
     1          (C2*V(2,7,ITIME)-C1*V(2,5,ITIME))**2+
     2          (C2*V(3,7,ITIME)-C1*V(3,5,ITIME))**2)
      DO 36 J3=1,3
      T1(J3)=X(J3,8,ITIME)-X(J3,10,ITIME)
      T2(J3)=X(J3,9,ITIME)-X(J3,11,ITIME)
   36 T3(J3)=X(J3,3,ITIME)-.5*(X(J3,1,ITIME)+X(J3,2,ITIME))
      V10Z=ABSF((V(1,10,ITIME)*T1(1)+V(2,10,ITIME)*T1(2)+V(3,10,ITIME)
     *         *T1(3))/SQRTF(T1(1)**2+T1(2)**2+T1(3)**2))
      V11Z=ABSF((V(1,11,ITIME)*T2(1)+V(2,11,ITIME)*T2(2)+V(3,11,ITIME)
     *         *T2(3))/SQRTF(T2(1)**2+T2(2)**2+T2(3)**2))
      V10Y=SQRTF(V(1,10,ITIME)**2+V(2,10,ITIME)**2+V(3,10,ITIME)**2
     *                        -V10Z**2)
      V11Y=SQRTF(V(1,11,ITIME)**2+V(2,11,ITIME)**2+V(3,11,ITIME)**2
     *                        -V11Z**2)
      VON=ABSF((V(1,1,ITIME)+V(1,2,ITIME))*T3(1)+(V(2,1,ITIME)+V(2,2,
     *         ITIME))*T3(2)+(V(3,1,ITIME)+V(3,2,ITIME))*T3(3))*.5/S(2)
      ED=ED+CONST*(VCHM**3*AHM+VON**3*AXN+AARM*(V1NM**3+V2NM**3)+AGLOV*
     1           (VH4M**3+VH5M**3)+AYBT*(V10Y**3+V11Y**3)+AZBT*
     2           (V10Z**3+V11Z**3))
      PMBRT=XMBRT(IT)-ED
      WRITE OUTPUT TAPE 42,75,TIME,XMBRT(IT),ED,PMBRT
   75 FORMAT(1P4E15.5/)
   80 CONTINUE
      GO TO 10
      END
```

```
*       JOB        X0621      Y.C. PAO
        SUBROUTINE ABC(AL,AS)
        DIMENSION FL(9),S(4),V(3,11,100),X(3,11,100)
        COMMON V,X
        COMMON ISEG,ITIME
        COMMON DAL,DAM,DAU,DLL,DLM,DLU,FL,S
        DIMENSION AL(3,9),AS(3,9),XAB(3),VBA(3),VO(3)
        DO 90 ISEG=1,9
        DO 15 I1=1,3
   15   AL(I1,ISEG)=0.
        GO TO (1,2,2,4,4,6,6,4,4),ISEG
    1   DO 105 IO=1,3
        XAB(IO)=X(IO,3,ITIME)-.5*(X(IO,1,ITIME)+X(IO,2,ITIME))
        VO(IO)=.5*(V(IO,1,ITIME)+V(IO,2,ITIME))
        VBA(IO)=VO(IO)-V(IO,3,ITIME)
        AL(1,ISEG)=AL(1,ISEG)+VBA(IO)**2
        AL(2,ISEG)=AL(2,ISEG)-VBA(IO)*VO(IO)
  105   AL(3,ISEG)=AL(3,ISEG)+VO(IO)**2
        GO TO 22
    2   IA=ISEG-1
        GO TO 8
    4   IA=ISEG
        GO TO 8
    6   IA=ISEG-3
    8   IB=ISEG+2
   11   DO 20 I2=1,3
        XAB(I2)=X(I2,IB,ITIME)-X(I2,IA,ITIME)
        VBA(I2)=V(I2,IA,ITIME)-V(I2,IB,ITIME)
        AL(1,ISEG)=AL(1,ISEG)+VBA(I2)**2
        AL(2,ISEG)=AL(2,ISEG)-VBA(I2)*V(I2,IA,ITIME)
   20   AL(3,ISEG)=AL(3,ISEG)+V(I2,IA,ITIME)**2
   22   AL(1,ISEG)=AL(1,ISEG)/FL(ISEG)**2
        AL(2,ISEG)=2.*AL(2,ISEG)/FL(ISEG)
        AS(1,ISEG)=((VBA(2)*XAB(3)-VBA(3)*XAB(2))**2+(VBA(3)*XAB(1)-VBA(1)
       *         *XAB(3))**2+(VBA(1)*XAB(2)-VBA(2)*XAB(1))**2)/FL(ISEG)**2
        IF (ISEG-1) 25,30,25
   25   DO 27 I3=1,3
   27   VO(I3)=V(I3,IA,ITIME)
   30   AS(2,ISEG)=(VO(2)*XAB(3)-VO(3)*XAB(2))*(VBA(3)*XAB(2)-VBA(2)*XAB(3
       1         ))+(VO(3)*XAB(1)-VO(1)*XAB(3))*(VBA(1)*XAB(3)-VBA(3)*XAB(1
       2         ))+(VO(1)*XAB(2)-VO(2)*XAB(1))*(VBA(2)*XAB(1)-VBA(1)*XAB(2
       3         ))
        AS(3,ISEG)=(VO(2)*XAB(3)-VO(3)*XAB(2))**2+(VO(3)*XAB(1)-VO(1)*XAB(
       *              3))**2+(VO(1)*XAB(2)-VO(2)*XAB(1))**2
        AS(2,ISEG)=2.*AS(2,ISEG)/FL(ISEG)
   90   CONTINUE
        RETURN
        END
```

```
*      JOB        X0622      Y.C. PAO
       FUNCTION CD(IT)
C      BEFORE CD EKPFRIMFNTAL VALUES RFCOHE AVAILARLE
C      SET CD=1
       CD=1.
       RETURN
       END
```

```
*      JOB       X0623      Y.C. PAO
       SUBROUTINE EQSOL(A,N,X)
       DIMENSION A( 3, 4),X(20),M(20)
       DO 9 I=1,N
       M(I)=1
       AMAX=A(I,1)
       DO 2 J=2,N
       IF (ABSF(A(I,J))-ABSF(AMAX)) 2,2,1
     1 AMAX=A(I,J)
       M(I)=J
     2 CONTINUE
       IF (AMAX) 3,98,3
     3 NN=N+1
       DO 4 J=1,NN
     4 A(I,J)=A(I,J)/AMAX
       DO 9 IP=1,N
       IF (IP-I) 5,9,5
     5 MMM=M(I)
       ZMULT=A(IP,MMM)
       DO 8 J=1,NN
       IF (J-MMM) 7,6,7
     6 A(IP,J)=0.
       GO TO 8
     7 A(IP,J)=A(IP,J)-ZMULT*A(I,J)
     8 CONTINUE
     9 CONTINUE
       DO 95 I=1,N
       NO=M(I)
    95 X(NO)=A(I,NN)
       GO TO 100
    98 WRITE OUTPUT TAPF 42,99
    99 FORMAT(12H NO SOLUTION)
   100 REJURN
       END
```

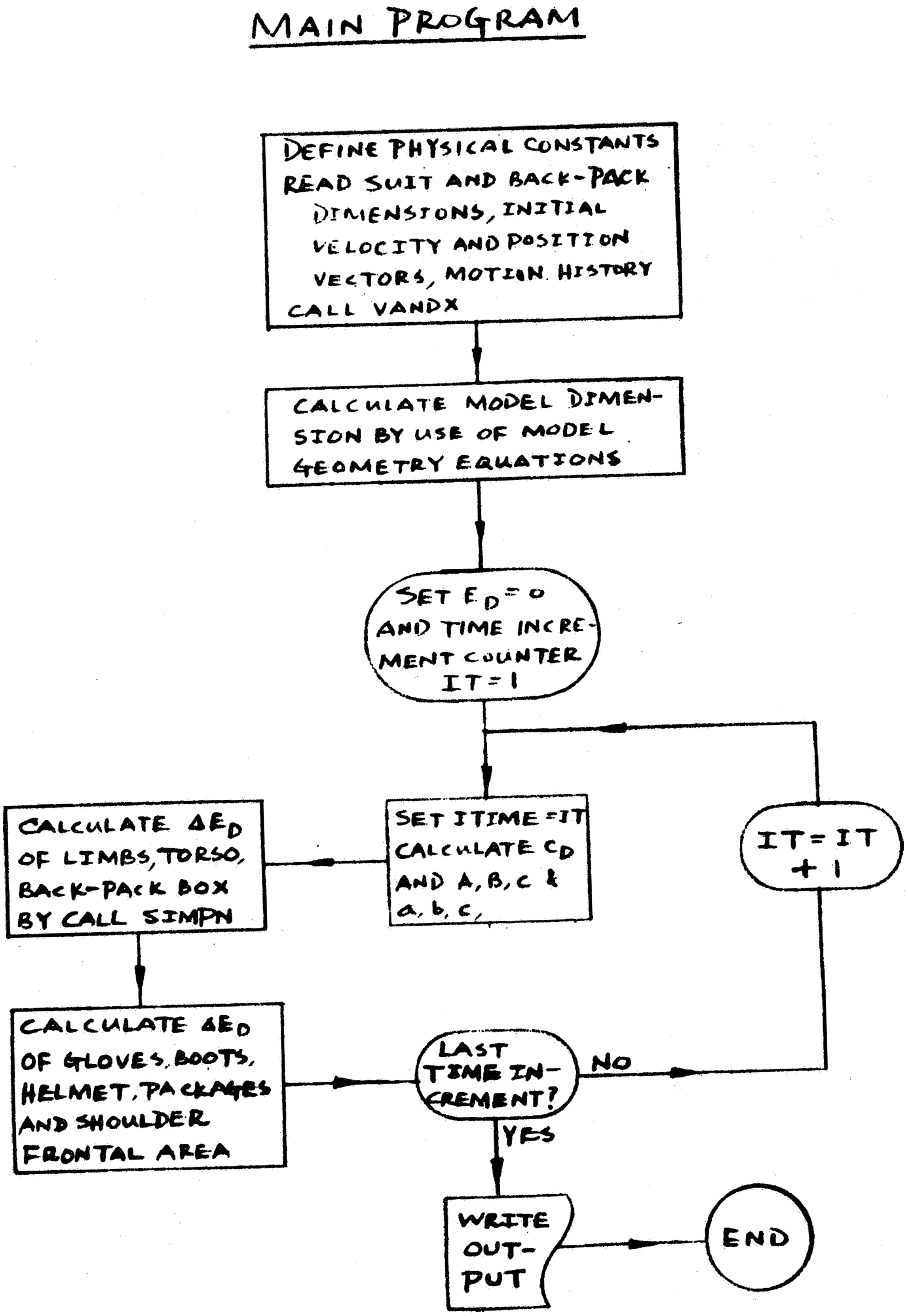
```
*       JOB       X0624      Y.C. PAO
        SUBROUTINE SIMPN(XL,NPT,NTIME,COEF,AL,AS,SUM)
        DIMENSION AL(3),AS(3),COEF(101)
        IF (NTIME-2) 30,30,40
     30 LEAP=1
        DO 38 I=1,NPT
        IF (I-1) 33,33,32
     32 IF (I-NPT) 35,33,33
     33 COEF(I)=1.
        GO TO 38
     35 GO TO (36,37),LEAP
     36 COEF(I)=4.
        LEAP=2
        GO TO 38
     37 COEF(I)=2.
        LEAP=1
     38 CONTINUE
     40 SUM=0.
        DL=XL/FLOATF(NPT-1)
        X=-DL
        DO 58 J=1,NPT
        X=X+DL
     58 SUM=SUM+COEF(J)*WABC(X,AL,AS)
        SUM=SUM*DL/3.
        RETURN
        END
```

```
*      JOB        X0625       Y.C. PAO
       SUBROUTINE VANDX(A,VO,XO,DT,NDT,V,X)
       DIMENSION A(3,1111001,VO(3,11),XO(3,11),DT(100),V(3,11,100),
      *          X(3,11,100)
       DO 20 IJ=1,11
       DO 10 IX=1,3
       V(IX,IJ,1)=VO(IX,IJ)+A(IX,IJ,1)*DT(1)
       X(IX,IJ,1)=XO(IX,IJ)+V(IX,IJ,1)*DT(1)
    10 CONTINUE
    20 CONTINUE
       DO 50 IT=2,NDT
       ITM1=IT-1
       DO 40 IJ=1,11
       DO 30 IX=1,3
       V(IX,IJ,IT)=V(IX,IJ,ITM1)+A(IX,IJ,IT)*DT(IT)
       X(IX,IJ,IT)=X(IX,IJ,ITM1)+V(IX,IJ,IT)*DT(IT)
    30 CONTINUE
    40 CONTINUE
    50 CONTINUE
       RETURN
       END
```

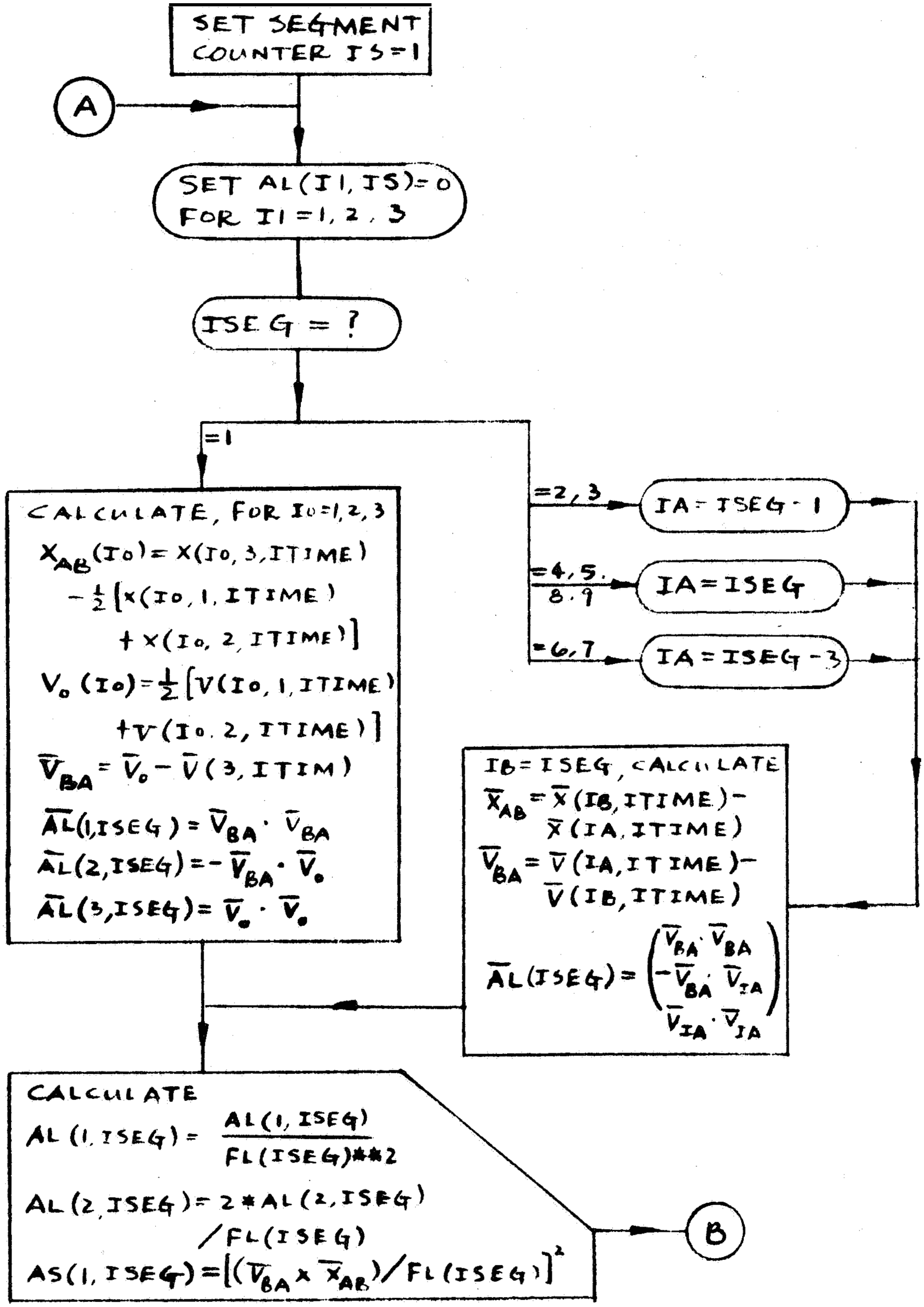
```
*       JOB         X0626      Y.C. PAO
        FUNCTION WABC(X,AL,AS)
        DIMENSION AL(3),AS(3)
        W=WX(X)
        WABC=W*(AL(1)*X**2+AL(2)*X+AL(3))*SQRTF(AS(1)*X**2+AS(2)*X+AS(3))
        RETURN
        END
```

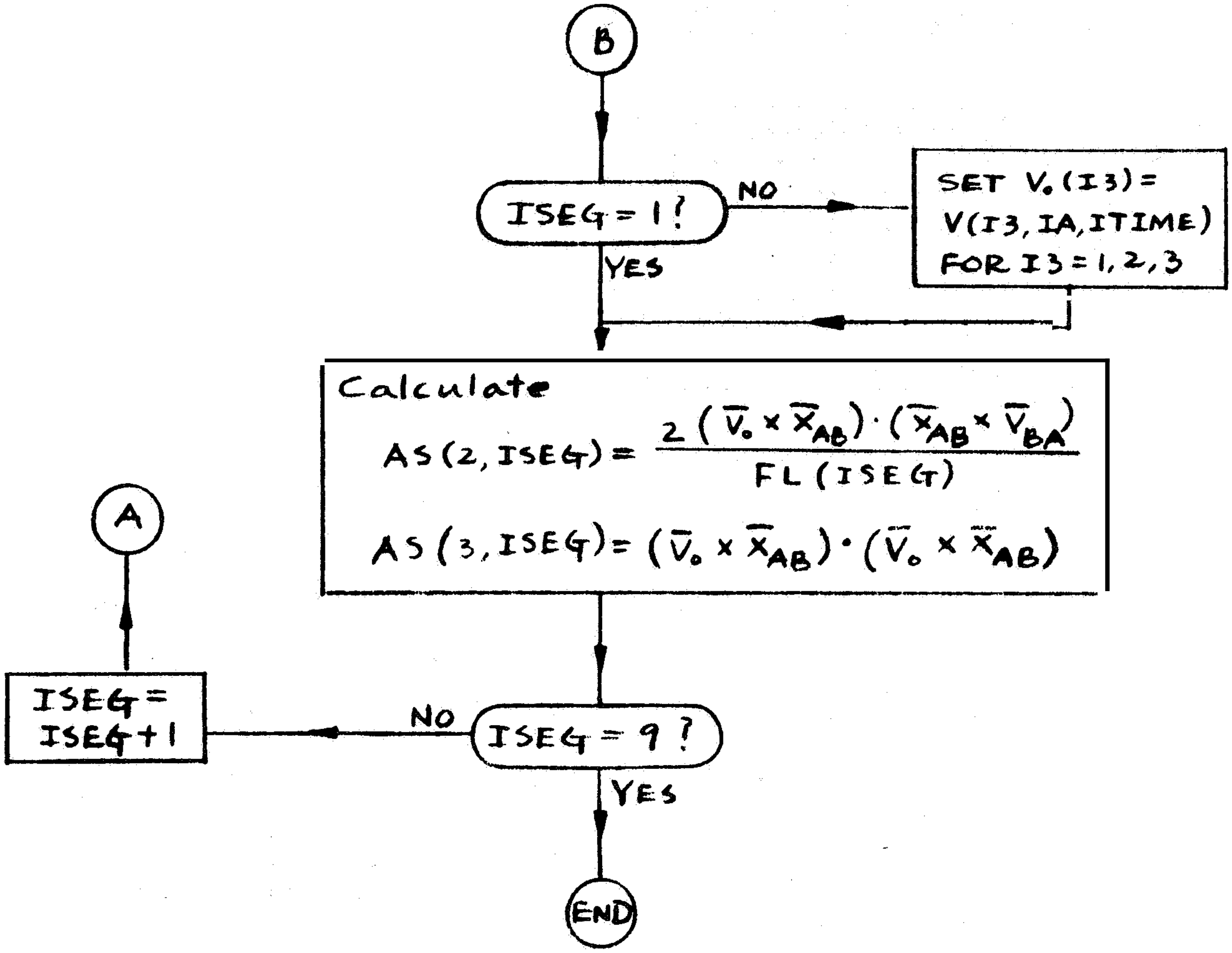
```
*      JOB        X0627      Y.C. PAO
       FUNCTION WX(Y)
       DIMENSION VX(3),X12(3)
       DIMENSION FL(9),S(4),V(3,11,100),X(3,11,100)
       COMMON V,X
       COMMON ISEG,ITIME
       COMMON DAL,DAM,DAU,DLL,DLM,DLU,FL,S
       GO TO (1,2,2,4,4,6,6,8,8),ISEG
     1 DO 13 I1=1,3
       VX(I1)   =(S(2)-Y)*(V(I1,1,ITIME)+V(I1,2,ITIME))/(2.*S(3))
      *          +Y*V(I1,3,ITIME)/S(2)
    13 X12(I1)=X(I1,2,ITIME)-X(I1,1,ITIME)
       VXM=SQRTF(VX(1)**2+VX(2)**2+VX(3)**2)
       COSFI=ABSF(X12(1)*VX(1)+X12(2)*VX(2)+X12(3)*VX(3))/(S(3)*VXM)
       WX=S(3)*SQRTF(1.-COSFI**2)+S(1)*COSFI
       RETURN
     2 WX=DAU-Y*(DAU-DAM)/FL(ISEG)
       RETURN
     4 WX=DAM-Y*(DAM-DAL)/FL(ISEG)
       RETURN
     6 WX=DLU-Y*(DLU-DLM)/FL(ISEG)
       RETURN
     8 WX=DLM-Y*(DLM-DLL)/FL(ISEG)
       RETURN
       END
```

PART 3. Flow Charts

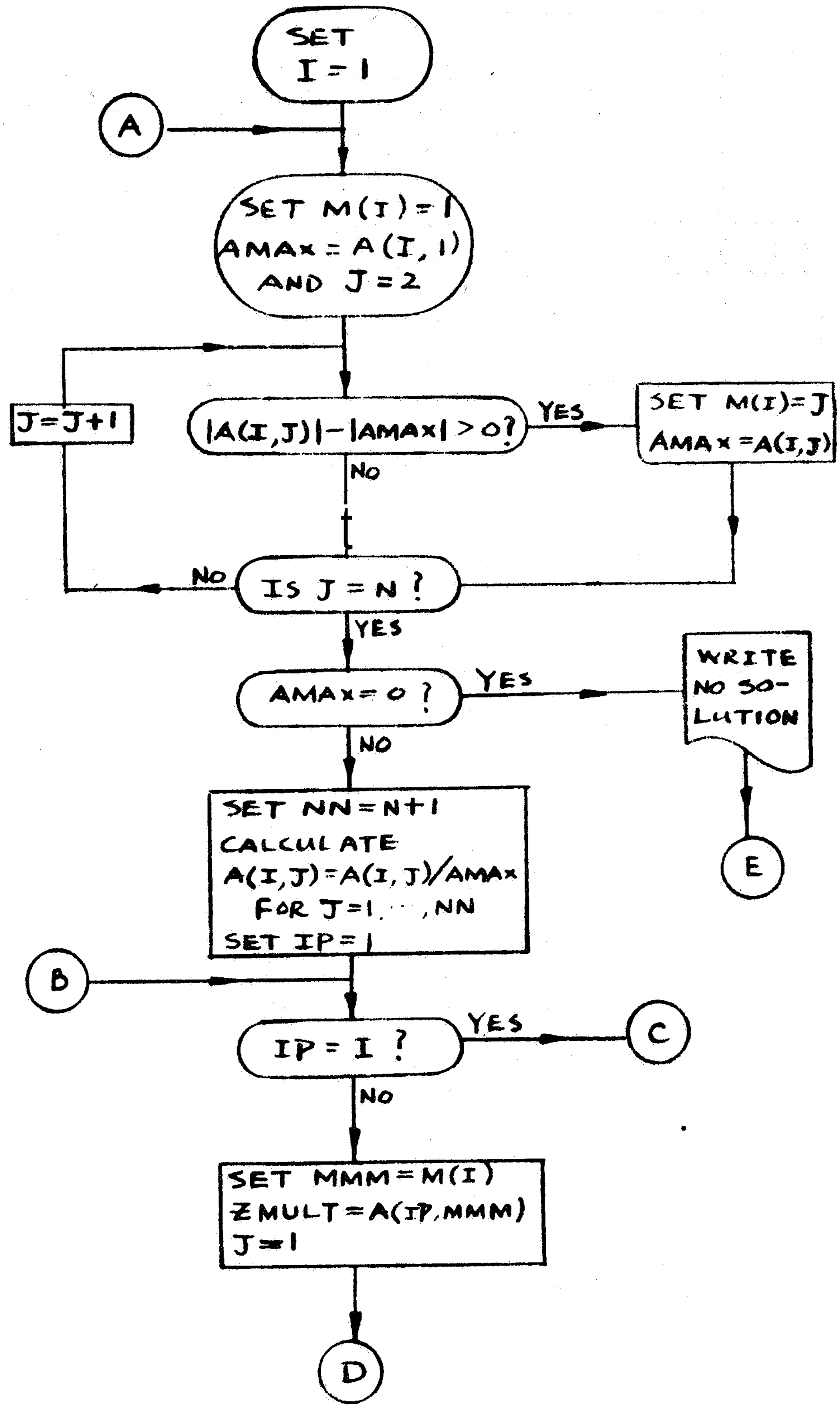


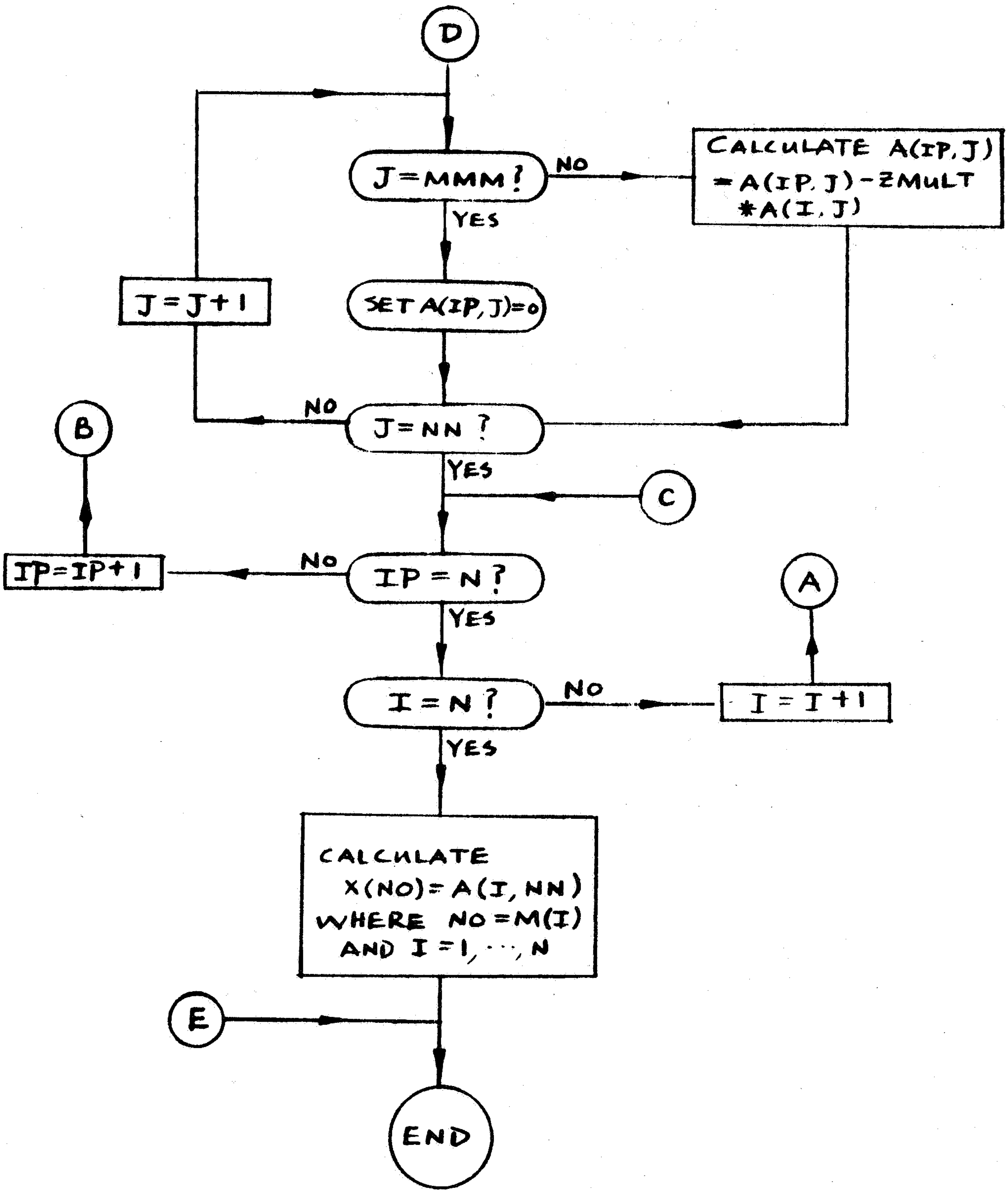
SUBROUTINE ABC



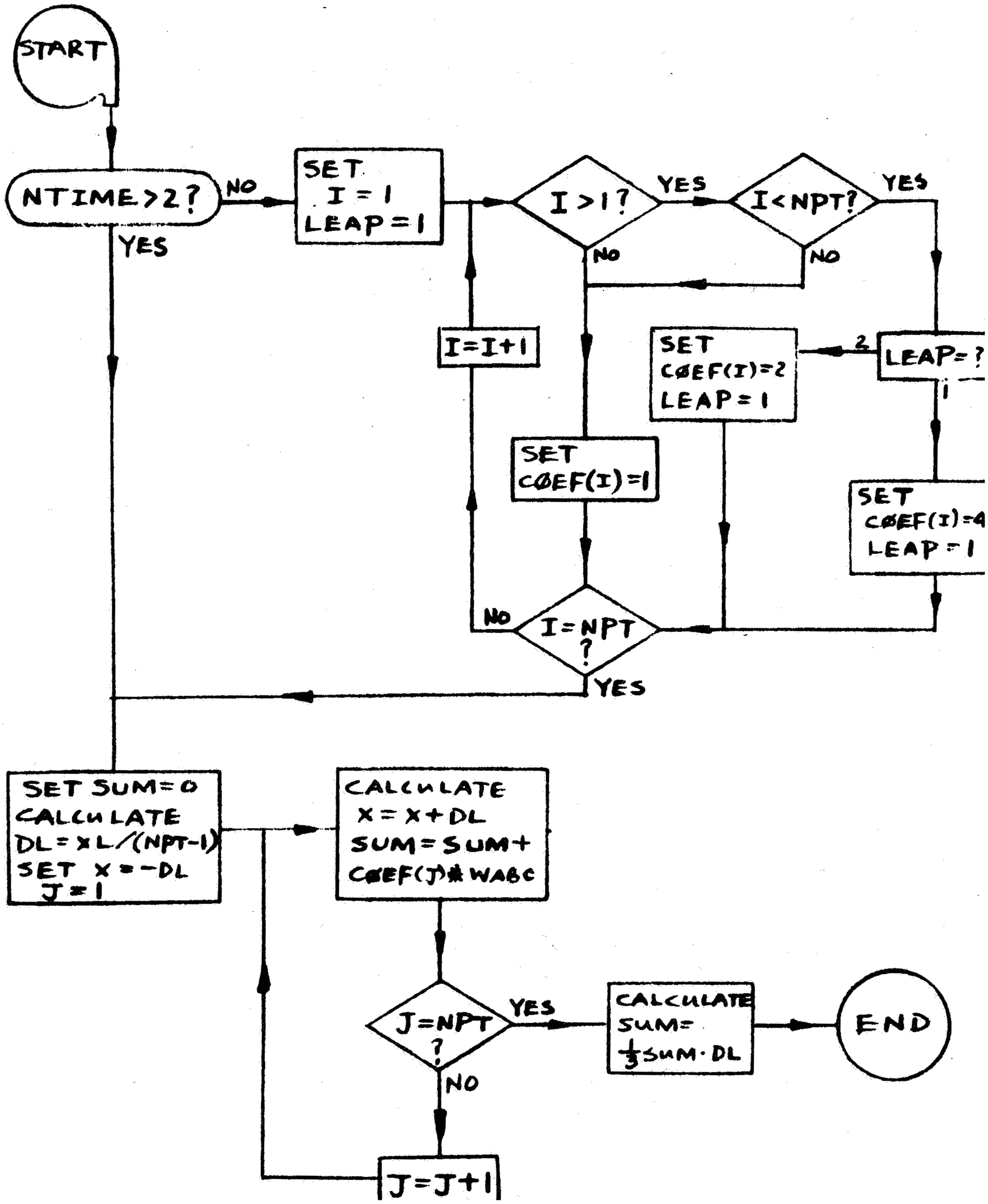

B
ISEG = 1?
NO
SET $V_0(I3) = V(I3, IA, ITIME)$ FOR I3 = 1, 2, 3
YES
Calculate
$AS(2, ISEG) = \dfrac{2(\bar{V}_0 \times \bar{X}_{AB}) \cdot (\bar{X}_{AB} \times \bar{V}_{BA})}{FL(ISEG)}$
$AS(3, ISEG) = (\bar{V}_0 \times \bar{X}_{AB}) \cdot (\bar{V}_0 \times \bar{X}_{AB})$
A
ISEG = ISEG + 1
NO
ISEG = 9?
YES
END

SUBROUTINE EQSOL

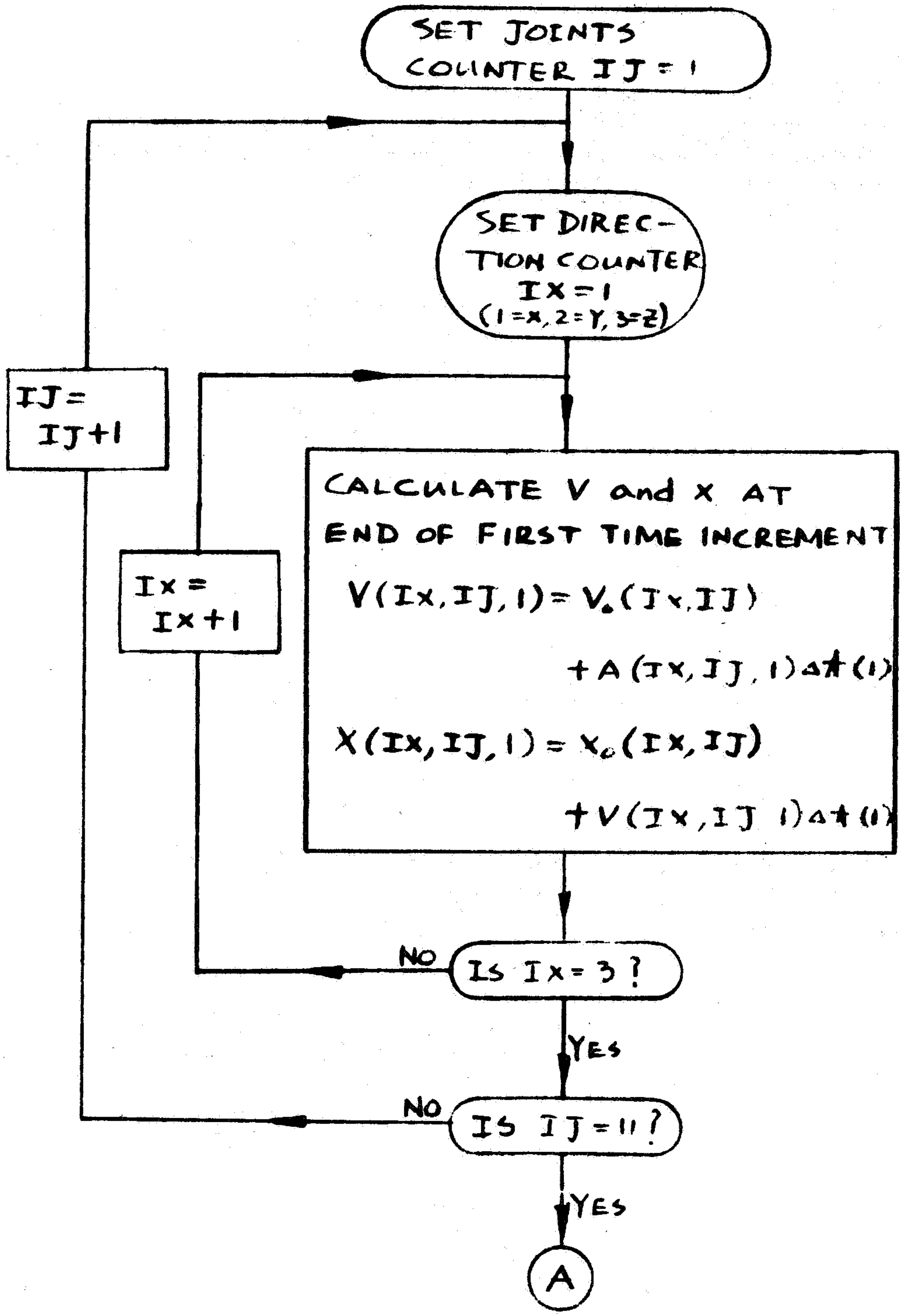


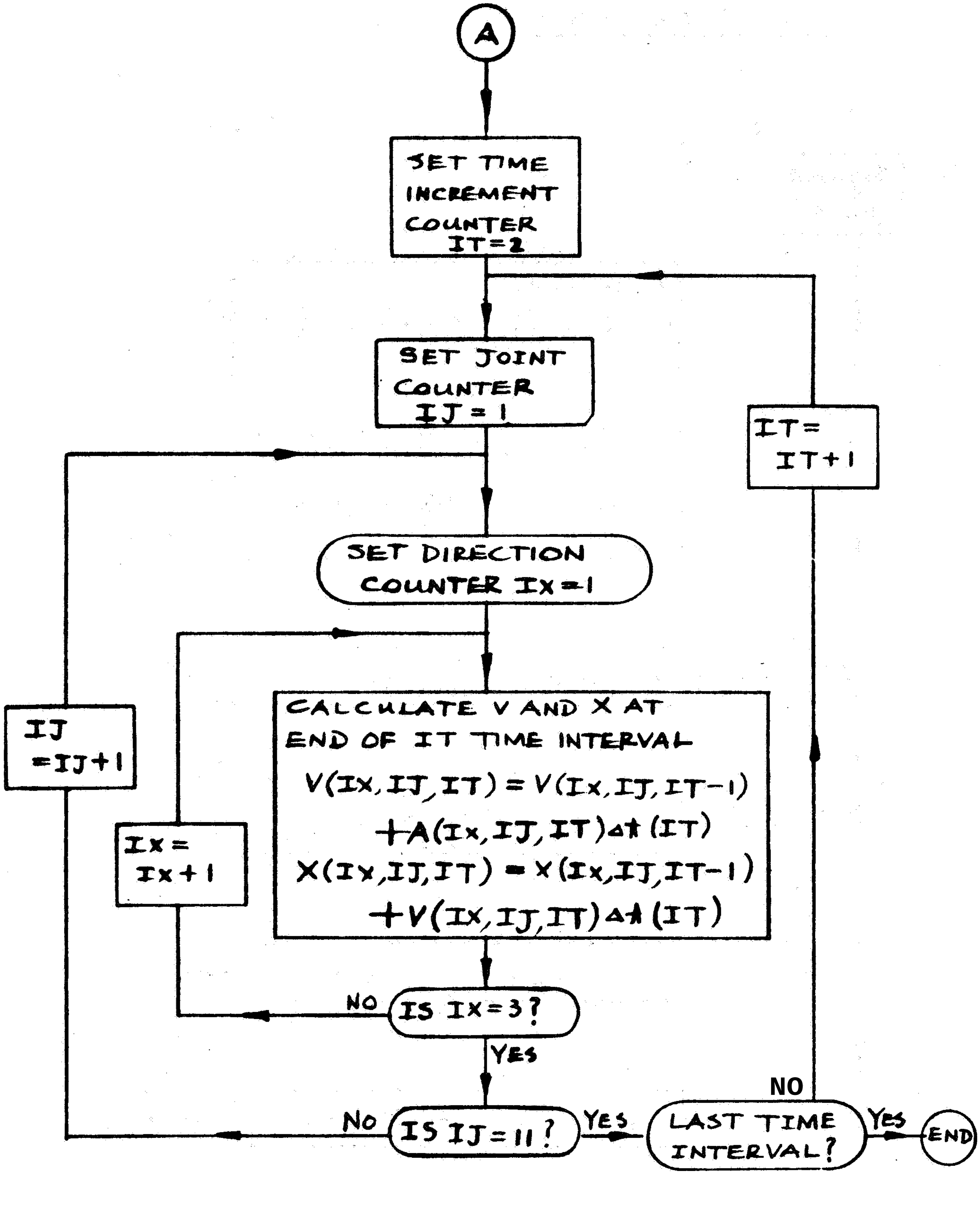

D
J=MMM?
NO
CALCULATE A(IP,J) =A(IP,J)-ZMULT *A(I,J)
YES
J=J+1
SET A(IP,J)=0
NO
B
J=NN ?
YES
C
NO
IP=IP+1
IP=N?
YES
A
I=N?
NO
I=I+1
YES
CALCULATE X(NO)=A(I,NN) WHERE NO=M(I) AND I=1,···,N
E
END

SUBROUTINE SIMPN

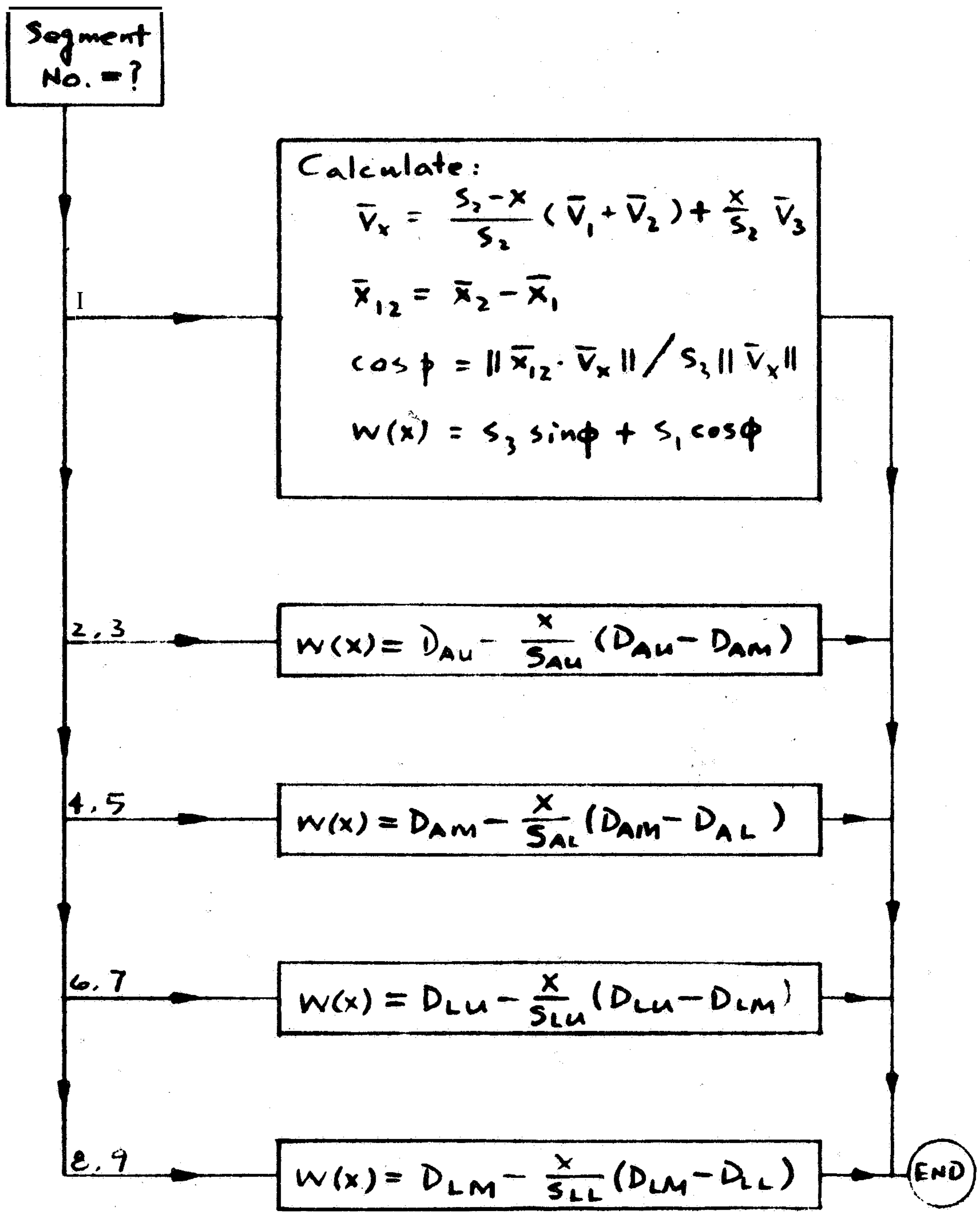


SUBROUTINE VANDX




A
SET TIME INCREMENT COUNTER IT=2
SET JOINT COUNTER IJ = 1
SET DIRECTION COUNTER IX = 1
CALCULATE V AND X AT END OF IT TIME INTERVAL
V(IX, IJ, IT) = V(IX, IJ, IT-1) + A(IX, IJ, IT)Δt (IT)
X(IX, IJ, IT) = X(IX, IJ, IT-1) + V(IX, IJ, IT)Δt (IT)
IS IX = 3?
NO
IX = IX + 1
YES
IS IJ = 11?
NO
IJ = IJ + 1
YES
LAST TIME INTERVAL?
NO
IT = IT + 1
YES
END

FUNCTION WX(x)



"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—National Aeronautics and Space Act of 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546